Human Research Program
Space Human Factors & Habitability Element

Evidence Book

Lack of Human-Centered Design

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National Aeronautics and Space Administration
Lyndon B. Johnson Space Center
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I. RISK GROUP: Lack of Human Centered-Design

A. PRD Risk Title: Risk of Reduced Safety and Efficiency Due to Poor Human Factors Design

Description: Inadequate human factors design in the physical work environments (e.g., vehicles, tools and tasks) will result in reduced human performance and increase the likelihood of errors. Research is needed to provide spaceflight human factors design data and design tools in microgravity and partial gravity.

B. PRD Risk Title: Risk of Error Due to Inadequate Information

Description: Operator errors are common in all work environments. Task errors during human spaceflight missions could have drastic consequences. Errors can be due to lack of information which in turn may be due to any of the following:

a) lack of situational awareness, which can be due to poorly designed interfaces, poorly designed tasks, or cognitive decrements due to, e.g., fatigue or exposure to toxic environments;
b) forgetting, which can be due to inadequate training, poorly designed procedures, or to cognitive decrements due to, e.g., fatigue or exposure to toxic environment;
c) inability to access appropriate data and procedures due to poorly designed interfaces, poorly designed tasks, or to cognitive decrements due to, e.g., fatigue or exposure to toxic environments; or
d) failure of judgment due to incorrectly perceived or interpreted cues, inappropriately estimated results of decisions, or inadequate data.

The risk is currently based on extensive data from commercial aviation, from nuclear power plant operations, and from other activities with high dependence on technology under sustained operations. The HRP must provide standards for reducing operator errors in spaceflight through adequate understanding of causes and mitigations of operator errors.

C. PRD Risk Title: Risk Associated with Poor Task Design

Description: Errors are often related to poor task design. Critical tasks must be designed to minimize operator error. Automation, feedback and other task design elements may be used in these cases. Multiple actors, including robots, present a unique risk.

II. Executive Summary of Evidence for Risks

Lack of Human-Centered Design

The risks of reduced safety and efficiency due to poor human factors design, error due to inadequate information and poor task design are elements of a greater root cause to the occurrences of human error, the lack of human-centered design. Human-centered design, or user-centered design, is a design approach that focuses on humans and their interaction with procedures, products, equipment, facilities, and environments. It seeks to utilize known information about human capabilities and develop designs to better match systems with human capabilities. This includes capitalizing on the strengths of the human in the system design, while limiting potential impacts resulting from human limitations. This design process focuses on the users throughout the planning, concept development, design, and final implementation phases of a product or a system (1). Utilization of a human-centered design process will aid in reducing elements of risk that can lead to human error within the human-machine system. Good human centered design practices will result in improved efficiency of operation and safety of all system components, including the human. However, the lack of a human-centered design approach directly contributes to the creation of three Space Human Factors Engineering (SHFE) risks (Figure 23-1).

To effectively illustrate the breadth and depth of the risks associated with a lack of human-centered design, the risk of reduced safety and efficiency due to poor human factors design, the risk of error due to inadequate information and risk associated with poor task design, the evidence from the past 50 years of spaceflight experience was carefully examined. In addition, where applicable, examples of ground based human engineering incidents related to the three SHFE risks are provided. This evidence will illustrate the extent to which these risks pose real threats with consequences of varying severity.

A. Risk of Reduced Safety and Efficiency Due to Poor Human Factors Design

The first and foremost goal of all human space exploration missions is to preserve the health and safety of the crew. Evidence associated with this risk clearly shows that poor human factors design can jeopardize operator safety and reduce operational efficiency. Concern for crew safety is the most critical aspect of human centered design and must be the primary design driver.

B. Risk of Error Due to Inadequate Information

Evidence relevant to the risk of error due to inadequate information illustrates that effective information management and communications are key to living and working successfully and safely in a given environment. The evidence illustrates that inadequate information can increase the probability of operator error, and a lack of information essential for performance of critical tasks could lead to lethal outcomes. As systems become more complex and compact, and successful performance of the spaceflight crew is critical, human-centered design becomes essential for effective information management and transfer to result in safe and productive missions.

C. Risk Associated with Poor Task Design

The evidence illustrating the risk associated with poor task design has shown that increasingly complex systems and longer duration missions have proven critical to ensure that the human-machine system, which includes all day to day operations, is less dependent on how well the human operates the system. Rather, the human-system interface and associated tasks are designed such that the system design solicits appropriate inputs from the operator. The human errors experienced in long duration spaceflight have been directly related to poor system and task design, including integration of the human into the end operational process. The evidence to follow has also shown that poor task structure or poor training can compromise the safety and effectiveness of the human-machine system.

D. Computer-Based Simulation Information

One of the difficulties associated with developing human habitats for remote environments and interfaces for complex systems is anticipating all of the operations that may be required. This is further complicated by user needs, specifically the needs of the user to successfully complete the operations are not always known. Therefore it is critical to have an understanding of how the human will integrate into a system and to identify risks that may be inherent in a concept or a design. Typically modeling is used to simulate remote environments and to evaluate design concepts for impacts to human safety and performance. This is in an effort to mitigate the risks associated with reduced safety and efficiency due to poor human factors design, error due to inadequate information, and with poor task design.

E. Risk in Context of Exploration Mission Operational Scenarios

Future exploration missions may last as long as three years. During this extended timeframe, crews will face the challenges of physical de-conditioning, prolonged isolation and confinement, significant communication delays with ground support, multiple changes in environmental stressors, and increased responsibility and autonomy. Utilizing good human-centered design techniques for vehicles, habitats and missions, is a significant tool for the management and control of risk of reduced safety and efficiency due to poor human factors design, risk of error due to inadequate information, and risk associated with poor task design associated with new longer duration missions.

F. Gaps

When there is a lack or break in information or knowledge associated with any given topic area or technology, it is considered a gap. With regard to the SHFE risks, a gap occurs when there is a break in the information continuum associated with prevention of the risks. It is important to identify these gaps and work to close them to prevent risks to the human and the mission.

During 2006 and 2007, analyses were conducted to determine which gaps relating to SHFE existed. The analyses included a review of literature and databases, subject matter experts and field users' interviews, as well as a full evaluation of the data gathered (2). These analyses helped to establish where additional research and information was needed to support future program development and extended research needs, including gaps associated with technology and application of available resources, processes and human integration needs, and hardware and tool support systems. All gaps identified directly contribute to the occurrence of the SHFE risks.

Each of the identified gaps that relate to the three SHFE risks can be attributed to one main component – poor human-centered design. Each aspect of the Human Centered Design Fault Tree (see Figure 23-1) has identified gaps in technology development, knowledge and processes where risks can occur. Without human centered-design, the gaps associated with poorly designed tasks and procedures, poorly designed hardware and systems, habitats and environments, a lack of task analysis and understanding of operations, the disregard for human-in-human machine system, the lack of an integrated system-design approach, and the lack of user evaluations and iterative design capture are all much more likely to occur.

III. Introduction

To fully understand why there are risks associated with the human in any design cycle, one must first acknowledge the human as a part of the system as a whole. When we look at a design in terms of a human systems integration approach, we see that careful consideration must be paid to the incorporation of human-centered design practices. Without particular focus on the human as the central component to the human-machine system, several human risks develop, specifically the three SHFE risks that can prove catastrophic if an incident were to occur.

In evaluating the evidence for the SHFE risks, a potential singular root cause for all three of the risks – the lack of human-centered design - was identified. In most, if not all of the spaceflight cases that demonstrate the reality of the risks, the absence of processes for assuring human-centered design was evident.

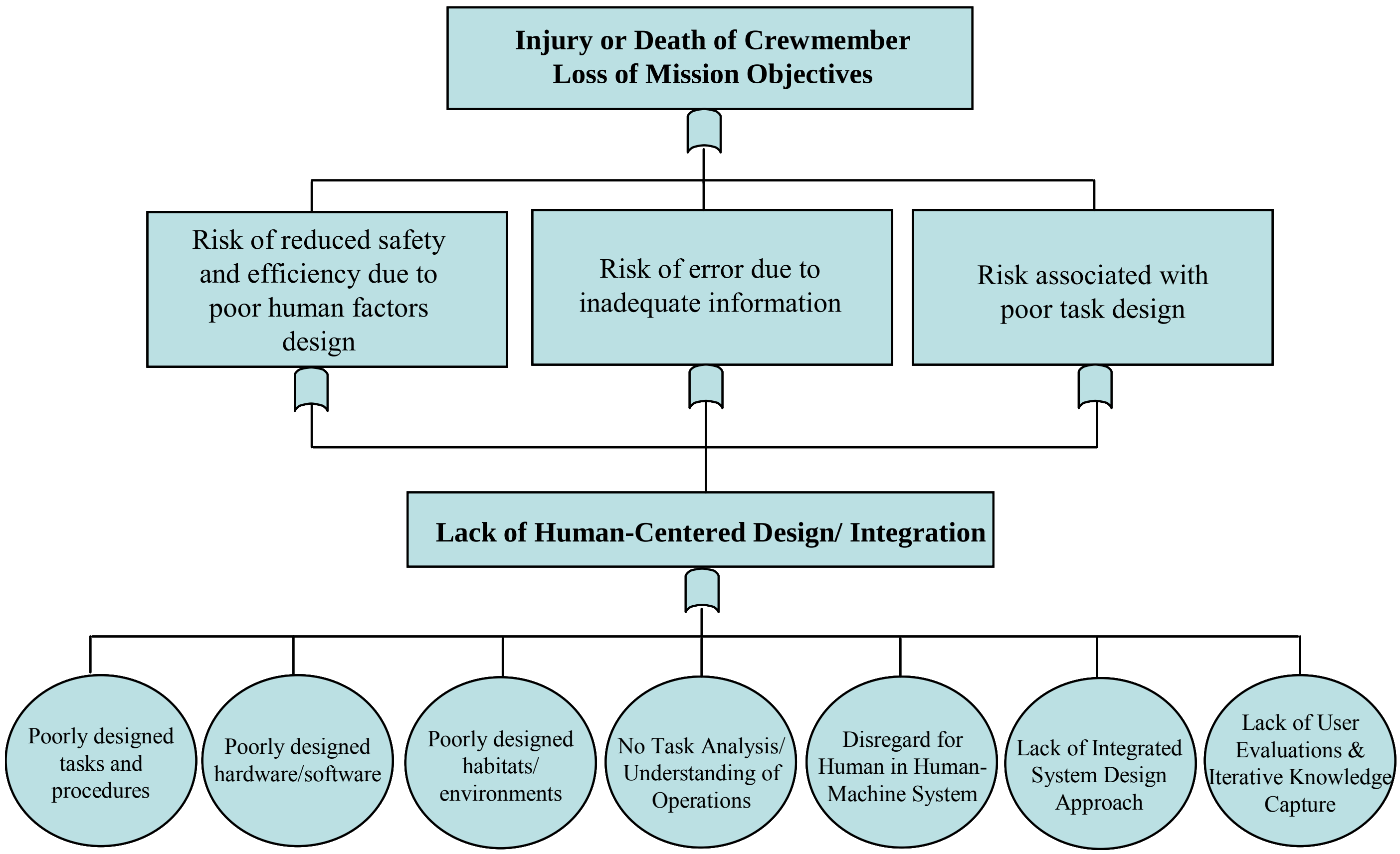

Figure 23-1. Lack of Human Centered Design Fault Tree (Concept adapted from 3)

The purpose behind human-centered design is to reduce the probability of injury or death of crewmembers, or the loss of mission objectives. As illustrated by Figure 23-1, there are multiple contributing components that can cause a lack, or poor, human-centered design, specifically: poorly designed tasks and procedures, designed hardware/software, habitats/environments, no task analysis/understanding of operations, disregard for the human in the human-machine system, lack of integrated system design approach, and lack of user evaluations and iterative knowledge capture.). As a result of the occurrence of the gaps associated with these components (e.g., poorly designed tasks and procedures and poorly designed hardware/software), a **lack** of a human-centered design approach has occurred. This leads to the introduction of the three SHFE risks which have the potential for negatively impacting the success of the mission and/or endangering the safety of the crew.

To further illustrate this point, an example is provided: consider a piece of hardware on which the crew is expected to perform maintenance in a short amount of time during their day. It requires the removal of a great number of screws to access behind a specific panel. Even with the proper tools, the task to remove all the screws is time consuming and requires the management of many small items simultaneously. The task takes longer than was expected or allotted to accomplish. This results in a reduction in crew efficiency, and possibly safety, which has an overall impact on goals and objectives for that time period. During the design development phase of the hardware it is critical to consider human centered design questions – was a task analysis performed to understand how the maintenance procedure was to be conducted? Could the design have required fewer screws to allow for a shorter time and easier access to the panel? Without using a human-centered design approach, and addressing the various aspects of the task expected of the crew, risk has been introduced against achieving the objectives of the mission and protecting the crew.

Reduced safety, increased errors and reduced efficiency are states that lead to potential loss of the human or mission objectives, the top of the tree in Figure 23-1. Good human-centered design should bring about desirable outcomes in the interaction of the human with the product, system or environment and reduce the overall risk for human error to occur, which includes the three SHFE risks (1).

The approach to presenting the evidence in Section IV is to provide the most appropriate examples for spaceflight and those that are ground-based to portray the issues. Therefore, a single example for spaceflight and a single example for ground-based evidence are provided for each of the issue topics that will be defined. Appendix A provides a listing of additional evidence examples that were investigated and support the risks. All associated references are listed in Section IX.

IV. Evidence

A. Details About the Evidence

1. Types of Data

The evidence presented within this document is taken primarily from data collected during 50 years of human spaceflight experience, with references to additional ground-based evidence, as applicable. Human factors research is heavily based in the behavioral sciences and with human spaceflight data collection there is an emphasis on multiple modes of observation and data collection. (4) **The primary mode of data collected is that of a descriptive and experiential nature**, astronauts debriefing their experiences from their spaceflights to the experts on the ground. This data is then logged and trended. The raw crew (astronaut) comments data, collected by the human factors experts, is logged in the International Space Station (ISS) Life Sciences Crew Comments Database (5). However, due to the sensitive nature of these raw comments, the data is protected and not publicly accessible. This is done to provide anonymity to the crew and to encourage continued open communication between the crew and ground personnel (e.g., Mission Control or other technical experts) postflight. This information is still utilized though, in a de-identified manner, by providing internal products that include ISS crew comments data requests, summary reports, lessons learned and published works. These information sources cover various topics areas, including but not limited to, architecture and topology; environment; stowage; human computer interaction; hardware and tool design and maintenance; procedures and training. These reports address the issues and trends within the associated topic area at the date of report generation, and cover experiences and majority findings for the lifetime of ISS. The reports are updated every two years to ensure current trends are reflected and a significant number of crewmembers have completed subsequent spaceflights and debriefs to justify the addition of data points. The database and reports are used to disseminate long duration lessons learned internally to NASA (e.g., to design teams), and externally (e.g., through published works) to strive for a closed-loop human-centered design approach. For the purpose of this evidence report, this type of data is viewed as a Category III data source.

The second most common data collection method is **crew hardware/system evaluations**, which can be both qualitative and/or quantitative with respect to the types of data obtained. As with experience data, crew hardware/system evaluations largely yield qualitative data. Similar to the ISS Life Sciences Crew Comments Database data sources, the data obtained during crew hardware/system evaluations are highly sensitive in nature and not publicly accessible. However, the data is logged in an ISS Crew Evaluations Database, much like the ISS Life Sciences Crew Comments Database. The information gained from the crew hardware/system evaluations is used to generate an evaluation results summary report, which details all major design and usability issues associated with the hardware/system at that particular point within the design life cycle. These summary reports are thoroughly reviewed with the design team and recommendations are made using these reports for improvements to the next phase of design for that hardware/system. The results are also presented in a forum, internal to NASA, at each design review meeting, Systems Requirements Review, Preliminary Design Review, Critical Design Review, and Systems Acceptance Review. For the purpose of this evidence report, this type of data is viewed as a Category III data source.

The third mode of data collection is **structured user testing**, where specific variables are being analyzed and the primary results are quantitative, but can also include qualitative aspects of evidence. These data sources are considered experimental in nature where the users testing environment and variables are either being manipulated or controlled in adherence with standard human behavioral research techniques (4). For the purpose of this evidence report this type of data is viewed as either Category I or II, depending on the specific testing protocol employed and data sought.

2. Data Collection Methods

Spaceflight data collection is continuous. This experiential data, unique to NASA operations for long-duration spaceflight, is collected at three different points in time during each mission: preflight, in-flight, and postflight.

Preflight is the time before a scheduled flight/mission during which many astronauts are asked to evaluate planned flight hardware. During preflight periods, the crewmembers and human factors experts can often evaluate the hardware/system for usability, maintainability, and its effects on habitability. The astronauts' evaluations are documented via verbal commentary, quantitative and qualitative questionnaires, photographs, or audio/video recordings.

In-flight refers to the period of time from launch until landing. During in-flight periods, personnel in the Mission Control Center (MCC) and the Mission Evaluation Room (MER; see below) provide on-console support for all onboard functions and tasks.

Postflight lasts a designated period beginning with landing. Until relatively recently, all crew debriefs are conducted postflight. These debriefs provide an opportunity for NASA teams (e.g., human factors, engineering, payloads, medical operations) to address mission/Expedition issues and collect detailed data. Typically, at the end of each ISS Expedition, lessons learned are documented and made available to the NASA.

Human factors data collection methods employed, during these three phases of flight, include:

- **Utilization of the Mission Evaluation Room (MER) Resources and Data**
  The MER provides near real-time on-console engineering and problem resolution support to the crew when systems or hardware issues occur with on-orbit systems or hardware. This resource will work real-time issues that may arise during day-to-day operations on ISS, providing interim and long-term resolution to problems. Human factors personnel participate as members of the MER team to obtain data and remedy problems real-time.

- **Participation in Crew Debriefs**
  Joint U.S and Russian postflight debriefs are held for ISS crews. Additional postflight debriefs are conducted with the U.S. crewmember. These individual debriefs provide an opportunity to follow-up on on-orbit issues and previous debrief comments, and collection of more detailed data. The data collected from this forum entered into the ISS Life Sciences Crew Comments Database.

- **Crew Evaluations**
  During crew evaluations, crewmembers and human factors evaluate hardware for its usability, maintainability, and its potential effects on ISS habitability. Crew evaluations are typically conducted with crewmembers ranging in experience (short duration, long duration, and no spaceflight experience), and/or gender and size (e.g., 5^{th} percentile female to 95^{th} percentile male). Feedback from the crew participants is documented through the use of quantitative and qualitative questionnaires, photographs, audio/video recordings, notes from the evaluation conductor and ultimately a formal summary report. The data collected from the crew evaluations are entered into the ISS Life Sciences Crew Evaluations Database.

- **Utilization of Questionnaires**
  Questionnaires are developed periodically to address specific concerns that have been raised during on-orbit operations or crew evaluations. Questionnaires are distributed to both experienced and novice crewmembers, and cover topics such as interface design, habitability, hygiene preferences, and issues with communication. The questionnaires are used to elicit comments from crewmembers on their operational experience, personal preferences, and suggested improvements. An example question is: *Do hygiene and privacy methods/products need to be improved if the duration of a mission extends to longer than 6 months?* The data collected from questionnaires are entered into the ISS Life Sciences Crew Evaluations Database.

3. Key Categories of Data Issues

Spaceflight evidence presented within this report is based upon the long duration spaceflight experience of U.S. astronauts living onboard the Russian space station Mir and the International Space Station (ISS).

Data from the ISS encompasses 15 Expeditions served by 19 U.S and 20 Russian crewmembers, to-date. The data is drawn from crew debriefs and "lessons learned" data that is tracked in the Mir and ISS Life Sciences Crew Comments databases. Comments entered into the databases are categorized by a topic area. Data has been trended over the lifetime of ISS. Overall, 940 comments pertaining to the Mir program and approximately 20,000 comments, pertaining to the ISS program, have been logged.

It is not the *number* of comments that drive issue identification - all comments, positive and negative, are logged. Issues are tracked across Expeditions and not by the number of times an issue is debriefed by each crewmember (e.g., one crewmember can highlight an issue multiple times across debrief sessions and this data will appear each time it was noted by the crewmember and at what debrief within the database). The issue will be tracked once per Expedition and not by number of times it is commented upon to avoid skewing occurrence of issues. Thus, the number of Expeditions citing an issue is much more critical than the number of times it has been commented upon.

The recurrence and relative significance of issues identified within the crew comments data have been tracked and the most critical "lessons learned" have been defined. Those issues that pertain to a Lack of Human-Centered Design/Integration have centered around six key elements shown in Figure 23-2.

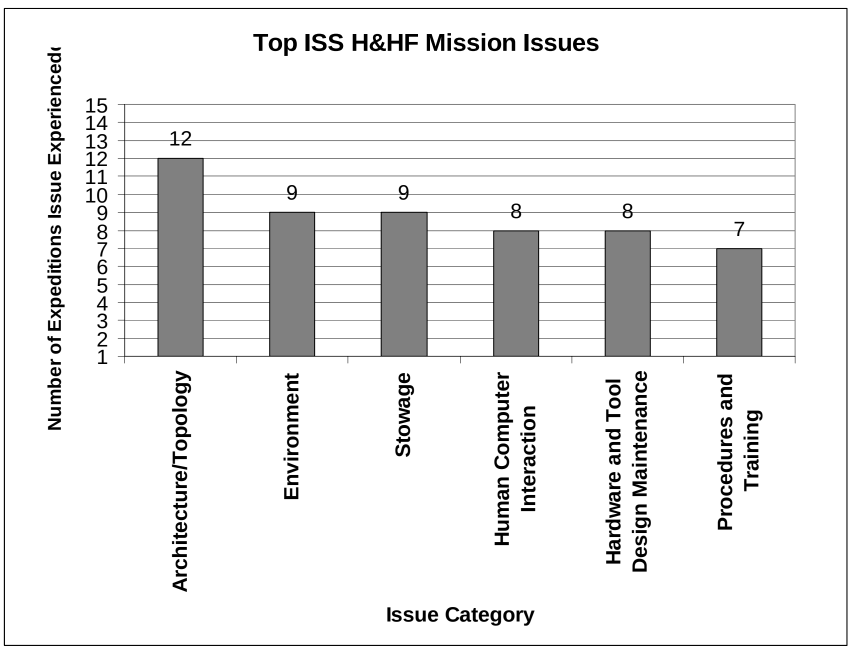

Figure 23-2. Reported ISS Expedition Habitability and Human Factors issues from postflight crew debriefs, showing the frequency of reported issues in each of the six categories.

- **Architecture/Topology**

  This category includes issues related to the design and configuration of the interior volume of the space vehicle. Problems documented in this category provide evidence for all three SHFE risks due to poor human centered design. Issues included here are those related to human translation and orientation information or problems that have occurred when spacecraft or spacecraft systems did not accommodate the crewmember anthropometry (size, shape, or strength).

- **Environment**

  This category identifies issues caused by different aspects of the spacecraft environment (e.g., radiation, noise, lighting). The problems documented in this category provide direct evidence of all three SHFE risks due to poor human centered design. The severity of the impact of this risk is dependent on the manner and extent to which the crew is exposed to certain elements of the environment.

- **Stowage**

  This category illustrates the problems related to the location and organization of stowage items onboard a spacecraft directly contribute to the three SHFE risks due to poor human centered design. Problems cited in this category are evidence of the risk of reduced safety due to poor human factors design. Problems will occur due to a lack of adequate stowage volume or poor stowage procedures, items that should be stowed remain in the spacecraft habitable volume and interfere with operations. Operations may also be impacted if stowed items cannot be easily located or identified. These problems become critical if contingency operations are impeded during an emergency event.

- **Human Computer Interaction**

  This category identifies issues related to the quality and commonality of software applications and display interfaces. Problems documented in this category provide evidence of each of the 3 SHFE risks depending upon the particular circumstances of the problem.

- **Hardware and Tool Design for Maintenance**

  This category identifies issues associated with the design of maintenance hardware. These types of problems provide direct evidence of the three SHFE risks due to poor human centered design. Problems with hardware design can have a significant impact on crew time and training. For instance, if the hardware has unique interfaces or if its maintenance requires a number of difference tools, on-orbit maintenance can cost an excessive amount of crew time.

- **Procedures and Training**

  This category addresses how safe, efficient, and successful a crewmember will be at tasks with the tools provided, specifically how the crew successfully learns and carries out their tasks. Any deficiency in tool design, procedure or training development for daily operations contributes directly to all three SHFE risks. With increasingly complex tasks and systems, clear and concise methods of information and skill transfer will be of paramount importance. Procedures have been a problem for the ISS crew because of their lack of usability and inadequate mode of information conveyance. This contributes to the risk of error due to inadequate information. This has caused many crews to disregard the validity of the procedures and contributed to noncompliance and incorrect execution of the procedure as written. Training is also impacted because the procedures are used as training tools to facilitate skill transfer. However, training has been a larger issue for the crew because the focus has largely been on mastering specific tasks, rather than the basic skills that can be applied to a broader collection of tasks, thus further contributing to the risk associated with poor task design.

B. Risk of Reduced Safety and Efficiency Due to Poor Human Factors Design

Spaceflight evidence has indicated that poor human centered design has compromised the performance and safety of the crew, as well as mission safety, effectiveness, and success. This in turn has directly contributed to the occurrence of the three SHFE risks, specifically the risk of reduced safety and efficiency due to poor human factors design. Evidence for ground-based issues surrounding poor human centered design can be seen in many areas of product development, from smaller items (e.g., cell phones, personal computers, home appliances) to larger products or structures (e.g., modes of transportation –auto and air – homes, or public buildings). The issues covered by the evidence have shown how poor human-centered design is at the core of the design development process and directly contributes to the occurrence of the three SHFE risks, specifically the risk of reduced safety and efficiency due to poor human factors design.

1. Architecture & Topology

Spaceflight Evidence

- *Example of Poor ISS Vehicle Interior Configuration (Category III [6])*
  The co-location of certain functional habitability areas has been problematic throughout long duration spaceflight. The adjacency of sleeping quarters with the waste and hygiene facilities has not proven optimal due to the noise made by the equipment that disrupts crew sleep. The co-location of dining facilities near exercise equipment and waste collection facilities has compromised sanitary and relaxing meals. In addition, locating dining facilities near laboratory work jeopardizes both habitability and the integrity of science activities. The integrity of science can be compromised by the introduction of foreign debris (e.g., food products) and can alter the results of the experiment by contaminating an environment that should be controlled. Frequently used translation passages have been blocked by large items, such as exercise equipment, which has contributed to congestion. The location of the dining table in a high traffic area has made translation difficult for the crew. In the past, these areas have been co-located due to lack of availability of on-board habitation volume and resources. However, due to the nature of living in space, this design concept has been sub-optimal and will not be beneficial for future space habitat designs because it presents numerous operational human hazards (Figure 23-3). This example illustrates that poor human factors design can have impact not only the mission objectives, but also create risk associated with the safety of the crew.

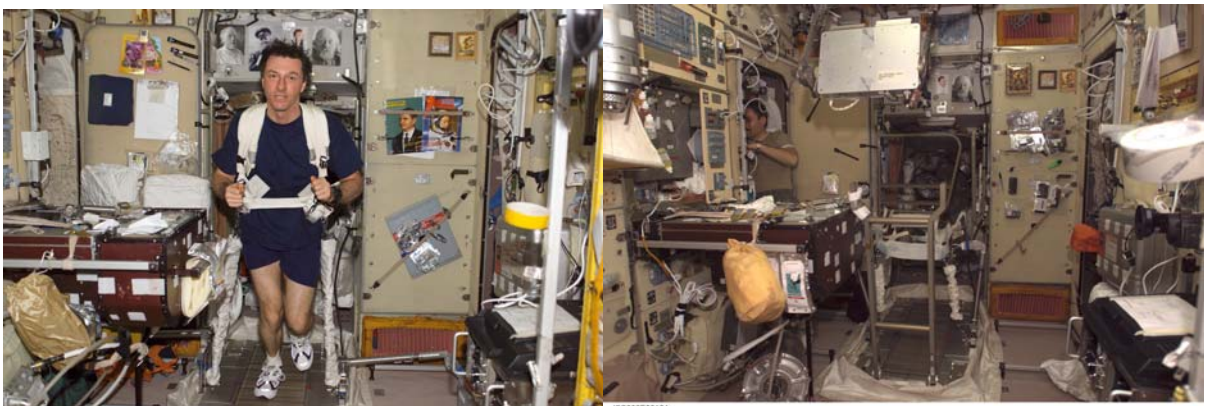

Figure 23-3. The two photos illustrate a poor ISS Service Module configuration with the galley, the treadmill, crew quarters, and waste and hygiene facilities co-located in the same habitable volume (Photos courtesy NASA[7]).

Ground-Based Evidence

- *Example of Inefficient Placement of Emergency Equipment (Category III [8]).* In 1912, over 1500 deaths occurred with the sinking of Titanic. While there were insufficient life-boats for all passengers and crewmembers, life-boat stowage was also a factor in the tragedy. On April 20, 1912, the New York Times published an interview a surviving Titanic wireless operator. He stated that he saw twelve men trying to get a boat to the deck and they were having "an awful time." A "steamship man" was quoted in the article as saying that a new law should include provisions for carrying boats in proper positions. While it is impossible to say exactly how many lives were lost due to the delays of un-stowing lifeboats, this was clearly a problem of poorly stowed items leading to unsafe conditions. This event has shown that architectural layout is critical to human safety. More importantly, this type of event is still remarkably current, as similar events have also occurred since this lesson had supposedly been "learned." (See Ground Based Evidence example, *Example of Poor Access to Stowed Lifeboats,* under the Stowage section within this risk).

2. Environment

Spaceflight Evidence

- *Example of Acoustic Noise Limits Exceedance (Category III [9, 10, 11]).* The ISS houses the crew, functions as their workshop and laboratory, and is where they spend all of their leisure time. The acoustic environment is complex with many types of noise-generating hardware. The cumulative effect manifests itself in two forms: continuous and intermittent noise. The continuous noise results from the operation of pumps, fans, compressors, avionics and other noise-producing hardware or systems. The intermittent noise is caused by hardware that operates cyclically, such as exercise equipment or the carbon dioxide removal system.

  Of the noise exposure measurements, approximately two-thirds exceed ISS requirements, and are 67 dBA or higher over a continuous twenty-four hour period and require the use of hearing protection. For work areas the levels must be no more than Noise Criteria curve (NC) 50 and for sleep areas it must be no more than NC 40, per ISS Program requirements. Most crewmembers choose to wear earplugs or noise-canceling headsets to mitigate the continual noise (Figure 23-4). Some do not adapt well to the constant irritation and discomfort of earplugs or the pressure of the headsets and prefer not to wear them. When communicating with the ground, the crew must increase the volume of the audio terminal unit (ATU) speaker to overcome the background noise. In addition, the crew's ability to communicate with each other is impaired; verbal communications only succeeds when both crewmembers are in the same module within a few feet of each other, and this is not an optimal or safe way for the crew to communicate. On a few occasions elevated noise levels have also prevented the crew from hearing caution and warning alarms and other monitoring signals. This was partially due to the crew's location within the ISS. The Node 1 module does not have its own ATU, and while in this module the crew must rely on hearing the nearby ATUs from the Lab and Airlock locations. At times it is difficult due to noise from exercise equipment and entertainment supports used while the crew exercises in Node 1. Risk to the safety of the human from over-exposure to environmental conditions directly contributes to successful and efficient mission performance.

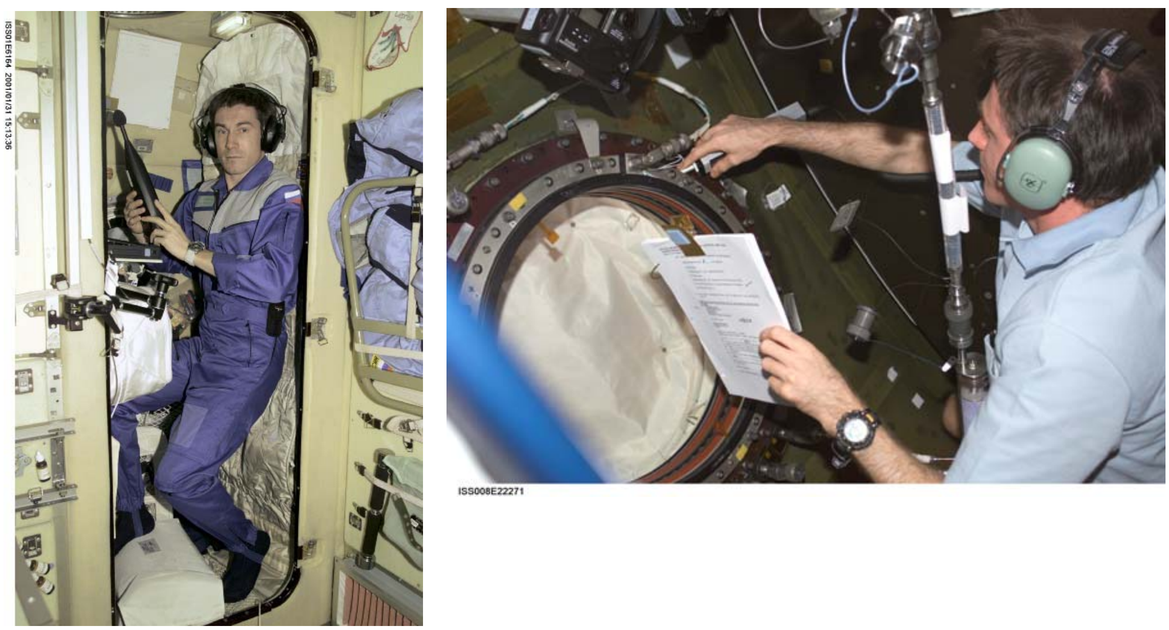

Figure 23-4. The two photos illustrate crewmembers wearing hearing protection devices and taking acoustic readings. (Photos courtesy NASA[7])

Ground-Based Evidence

- *Example of Insufficient Lighting (Category III [12,13]).* In 2003, 100 people were killed trying to escape a fire at The Station night club in West Warwick, Rhode Island. When the fire started, the lights went out and most of the panicked crowd rushed to the only exit they knew - the entrance to the club. Although there were three other exits, few used them and the main entrance became quickly blocked. The Fire Chief said the exits had signs with battery-powered lights, but they were too dim for people to see them through the smoke. Sufficient lighting should have been provided, and potentially more people would have found the alternate exits, reducing the crowd at the main doors. Safe operations of the club demanded proper lighting for emergencies. This evidence provides an example of where the environment lighting did not meet human needs and directly contributed to unsafe and inefficient conditions which resulted in injury and death.

3. Stowage

Spaceflight Evidence

- *Example of Accessibility to Interior Components (Category III [9]).* With the mounting stowage problems, there is a need to stow items in front of panels and in translation paths decreasing the crew's ability to access items quickly. Cable routing also blocks access to panels and stowage locations. In addition to accessibility problems caused by obstructions, the crew has also experienced accessibility problems due to the design and integration of hardware. The interior components of the U.S. segment of the ISS are grouped into a series of "racks" which were designed to rotate, or tip over, to provide crew access to the rack utility connections and the module wall. However, crew feedback has indicated that rotating the racks is not an effective way to access utilities and connectors in a microgravity environment. The clearance required for human accessibility was repeatedly cited as an issue to rack rotation capability. The design of the panels and drawers with these racks have compromised crew accessibility because many of them "stick" on-orbit due to the design not operating as intended in 0-G, or there are too many items placed within these stowage locations and not organized to afford easy operation. Finally, overall topology negatively affected crew accessibility. As an example, the U.S. cycle ergometer blocks access to the Lab window. Physical and visual access to on-board windows has been very important to the crew for their habitability and mental health (Figure 23-5). Restricted access and blocked translation paths contribute negatively to the overall safety and efficiency of the crew, and can lead to dire circumstances in the event of an emergency.

Figure 23-5. The two photos illustrate accessibility issues caused by stowage placement and location of items in high activity areas, such as the cycle ergometer on the left (Photos courtesy NASA[7]).

Ground-Based Evidence

- *Example of Poor Access to Stowed Lifeboats (Category III [14]).* The cruise ship Lakonia departed Southampton, England on December 19, 1963 for a Christmas cruise to the Canary Islands. Four days into the cruise, a fire broke out that could not be contained. As a result, a total of 128 people died on the Lakonia, 53 in the actual fire, and the rest from exposure, drowning and injuries sustained while diving overboard. Because of poor access to the stowed lifeboats, evacuation of the ship was extremely difficult. Some lifeboats burned before they could be lowered. Two of the lifeboats were swamped, spilling their occupants into the sea; one when it was lowered only by one end, and the other when the lifeboat davits broke. Chains had rusted on many of the davits, making boats difficult or impossible to move. Ultimately, just over half of the lifeboats made it safely away from the Lakonia, some of them filled to less than capacity. Had accessibility and upkeep to these stowed life boats been considered, additional deaths would have been avoided. Similarly to the Titanic, the chosen stowage locations for life boat provisions directly contributed to reduced safety of the crew during the fire and caused additional deaths.

4. Human Computer Interaction

Spaceflight Evidence

- *Example of Computer Failures (Category III [15]).* On April 23, 1967, immediately after orbital insertion of the Russian Soyuz 1 vehicle, one of the solar panels failed to deploy and remained wrapped around the Service Module. Although only half of the solar power necessary was being received, an attempt to maneuver the spacecraft was made. The manual maneuver failed due to interference of the spacecraft's reaction control system exhaust with the ion flow sensors, one of Soyuz's main methods of orientation.

  The decision was then made Russian ground control to bring Soyuz 1 home. However, the first retro fire (used to prepare the spacecraft for re-entry) failed because the spacecraft was going through an ion pocket, an area of low density where the sensors were unable to detect the direction of motion of the vehicle. The next decision made was for a manual retrofire on the next orbit, occurring on the night side of the Earth. This made it impossible for the crewmember to use the Vzor optical alignment device to orient the Soyuz for reentry, and the decision was made to align by sighting the Moon through the periscope.

  Re-entry was successful and the drag chute deployed, but due to a failure of a pressure sensor the main parachute wouldn't deploy. The reserve chute was released but became entangled on the drag chute, which normally would have been released with deployment of the main chute. The spacecraft crashed into a field in Orenburg, Russia, killing the crewmember (Figure 23-6).

  The computer navigation instrument design never considered a failure that would take out the solar power supply. Multiple serial failures within the navigation system could have been prevented with the design of additional redundancies. This would have reduced the reliance on manual maneuvers, if there had been a fully-operating redundant automation feature. Environmental susceptibilities of the sensors weren't fully considered for functionality within an ion pocket and no secondary system was in place for the pressure sensor failures to ensure safe operation of the chutes, thus reducing the overall safety of the crew.

Figure 23-6. Photo of the Soyuz 1 crash site and the remains of the Soyuz vehicle after the accident. (Photo courtesy of NASA[7])

Ground-Based Evidence

- *Example of Incorrect Critical Data Parameters (Category IV [16])*. On March 11, 2005, Airbus A321-231, registration GMEDG, attempted to land at night in Khartoum, Sudan in dust storm conditions. A runway was in use, but the instrument landing system (ILS) on this runway was out of service. The commander felt they were permitted to land on this runway via a managed non-precision approach (MNPA) that requires the autopilot approach path stored in the aircraft's flight management and guidance system (FMGC) navigation database. The final descent point on the pilot's approach chart differed from the FMGC's correct approach point.

  The pilot began their approach with the autopilot engaged. The aircraft began its final descent later than expected. The handling pilot felt the aircraft was high on approach and changed the autopilot mode in order to select an increased rate of descent. This caused the approach to become unstable and the aircraft descended at an abnormally high rate. While passing through the minimum descent altitude, neither pilot established visual references for landing and they both incorrectly assumed the other had visual contact with the runway approach lights. When they realized what had happened, the plane had descended to 180 feet above ground level and a go-around was initiated. The enhanced ground proximity warning system (EGPWS) then annunciated an audio warning "TERRAIN AHEAD, PULL UP." The emergency pull up procedure was not followed in full because the go-around had been initiated. The minimum recorded terrain clearance achieved during the recovery maneuver was 121 feet. The crew attempted a third approach, but received visibility information from air traffic control (ATC) that was below minimum for approach and the aircraft was diverted for landing at another airport.

  One of the critical causal factors in the above incident was that the pilots were unaware of a significant discrepancy in the information provided to them between the approach parameters on the approach chart and those in the navigation database. These two sets of data were mistakenly displayed to the pilots and not compared before approach attempts were made. Confusion related to the correct approach profile and inappropriate autopilot selections led to an unstable approach and reduced crew safety and efficiency.

5. Hardware and Tool Design and Maintenance

Spaceflight Evidence

- *Example of Incorrect Use of Hardware (Category III).* Dr. Jon Clark's presentation at the Houston Chapter of the Human Factors & Ergonomics Society in April 2006 illustrated where a pressure loss occurred due to a flexhose leak on a window assembly on ISS. The Human Factors Requirement for window workstations stated: "Design and placement of window workstation restraints shall allow up to four continuous hours of comfortable use." The flexhose jumper function was a part of the window assembly that ensured that a vacuum was maintained between the U.S. Lab window primary and redundant pressure panes. The flexhose did not meet the ISS handhold requirement as it was never intended to be a handhold. However, its final design implementation and location within the ISS internal volume was such that it facilitated use as a handrail to the crew (Figure 23-7).

  The crew's use of the flexhose as a handhold created stresses that were the most probable cause of the leak and risk to human safety. The hardware created a situation where the design effectively conveyed additional usage to the crew at that task area. Environmental design cues may often contribute to how a task design is ultimately communicated to the operator. In this case, the safety of the mission and the crew were put in jeopardy by the additional cues the hardware design provided the crew.

Figure 23-7: This photo depicts a crewmember conducting maintenance on the ISS Lab window. (Photo courtesy NASA[7])

Ground-Based Evidence

- *Example of Poorly Placed Fuel Selector (Category IV [17, 18]).* "On October 12, 1997, about 1728 Pacific daylight time, an experimental category, amateur-built Adrian Davis Long-EZ airplane, N555JD, crashed into the Pacific Ocean near Pacific Grove, California. Air traffic control communications indicated that the airplane had departed from the Monterey Peninsula Airport's runway 28L about 1712 hours and the pilot performed three touch-and-go landings and departed to the west moments before the accident. Witness reported that they heard engine popping and a reduction in engine noise before the accident. The pilot made no distress calls. The pilot was killed, and the airplane was destroyed.

According to the designer of the airplane and the drawings issued to the builder, the fuel selector is to be located just aft of the nose wheel position window between the pilot's legs. The accident airplane's fuel selector handle was positioned by the builder on the bulkhead behind the pilot's left shoulder. The selector valve was installed inside the engine firewall 45 inches aft of the selector handle. The handle and valve were joined by steel and aluminum tubing, connected by a universal joint. According to other pilots who were familiar with the airplane and/or had flown it, to change the fuel selector a pilot had to: 1) Remove his hand from the right side control stick if he was hand flying the aircraft; 2) Release the shoulder harness; 3) Turn his upper body 90 degrees to the left to reach the handle; and 4) Turn the handle to another position.

The National Transportation Safety Board determined the probable cause of this accident was the pilot's diversion of attention from the operation of the airplane and his inadvertent application of right rudder that resulted in the loss of airplane control while attempting to manipulate the fuel selector handle. Also, the Board determined that the pilot's inadequate preflight planning and preparations, specifically his failure to refuel the airplane, was causal. The Board determined that the builder's decision to locate the unmarked fuel selector handle in a hard-to-access position, unmarked fuel quantity sight gauges, inadequate transition training by the pilot, and his lack of total experience in this type of airplane were factors in this accident." Although there were multiple causal factors at work, it is clear that poor design and operational management lead to direct risks to the operator's safety and efficiency in operating the aircraft.

6. Procedures and Training

Spaceflight Evidence

- *Example of Lack of Emergency Response Plan and Procedures (Category III* [15, 19]*)* On January 27, 1967, when the Apollo 1 crew initiated what should have been a nominal countdown drill, disaster struck. Fire erupted in the command module and panicked cries of "Fire" were heard from the Kennedy Space Center's Pad 34. All three crewmembers lost their lives because they were unable to open the hatch and escape the command module to safety. Many factors contributed to this incident including (Figure 23-8):
    - The insulation on a live electrical wire had been worn and torn in an environment of 100% oxygen, high internal pressure within the module.
    - The inadequate hatch design (hatch was designed to open in, which was impossible for a human to open given the pressure levels within the vehicle).
    - Little consideration had been given to risks and hazards associated with any of the preflight activities, only those pertaining to space-flight. Due to the fact that little thought had been given to the reality of a hazardous event on the ground preflight, NASA had not developed procedures or processes on how to deal with an emergency event.
    - The lack of process and procedures was evident in that there was no fire rescue or medical teams at the launch pad during the drill. Procedures were critical because the work space layout included multiple levels around the space vehicle with steps, sliding doors and sharp turns that hindered easy emergency response.

The direct lack of appropriate procedures and human-centered design decisions contributed to the unsafe situation where the crew was exposed to and resulted in their deaths.

Figure 23-8. The photos depict the Apollo 1 crew prior to the tragic fire and the vehicle after the fire (Photos courtesy of U.S. Centennial of Flight Commission[20])

Ground-Based Evidence

- *Example of Poor Execution of Process Procedures (Category III [21])*

The Chernobyl nuclear meltdown disaster exhibits how poor human factors design resulted in the reduction of safety and loss of human life. The incident was the result of a direct violation in which operators intentionally "experimented" with the plant at unsafe operating conditions.[22] During routine operations the plant would have normally been shut down for this test. During this incident, however, operators were instructed to operate the reactor at lower power levels in order to avoid the reactor being offline.

The personnel performing the operation did not have the proper training to perform this procedure. According to the official reports six important safety devices were deliberately disconnected on the night of April 25, the day before the accident. The most important of these devices was the emergency core cooling system. The reactor was deliberately and improperly run below 20% power. This violation in safety procedures and the lack of operator training led to a chain of events that ultimately resulted in the reactor meltdown. If the designers of Chernobyl had anticipated the off nominal operation of the reactor and integrated the appropriate human factors considerations into the design of the reactor, the event may have been averted and the safety of the personnel preserved.

C. Risk of Error Due to Inadequate Information

Spaceflight evidence indicates that inadequate information can compromise crew and mission safety and effectiveness. On the ground, operator errors due to a lack of information occur frequently and can have severe consequences. Inadequate information may be attributed to poor interface design, poor training or procedures, or poor information seeking behavior. Integration of human-centered design ensures that operators receive the necessary information in the appropriate formats to complete tasks successfully, efficiently, safely and reduce the risk of error. Evidence provided below illustrates examples of errors due to lack of information in various ground based environments.

1. Architecture & Topology

Spaceflight Evidence

- *Example of a Lack of Necessary Vehicle Docking Data (Category III [23]).*

In June 1997, the Russian spacecraft Progress 234 collided with the Mir space station causing a pressure hull rupture and nearly causing the abandoning of the Mir (Figure 23-9). Analysis post-incident found a number of contributing factors including: the condition of the vehicle, the workload of the crew, continuous attention, and the crash.

Prior to the event, there was concern regarding interference that might be caused by the Kurs radar system during Progress 233 and the decision was made to shut the system down during Progress 234, but the result of this action deprived the crew of necessary range data. It was later determined that there were three immediate causes for the crash: a higher than planned initial closing rate, late realization that the closing rate was too high, and incorrect final avoidance maneuvering.

The human factor that played a part in the incident was the stress the crew experienced due to the repeated systems failures which continuously commanded their attention and contributed to reduced vigilance capabilities for the crew. Ellis cites that there was a potential that several aspects of human factors might have been a large contributor to this incident, such as: psychophysical factors (low contrast and poor resolution of the manual docking system TV display), sensorimotor factors (the dynamics and frame of reference for the tele-operation of the Progress and the difficulty the crew had determining relative velocity from visual TV information), and cognitive factors (the shut down of the Kurs radar took away the crew's position, range and range rate information, decreasing the ability to keep spatial awareness).[23] In addition, the last formal training the crew received was four months previous to the docking event, and there may not have been sufficient or timely practice to face the conditions. After the Progress collision with Mir, the emergency situation required closing the hatch of the module that was leaking air, and this task took extra time because cables running through the open hatch did not have easily operable disconnects and they had to be cut.

Although multiple factors contributed to the event, the reduced situational awareness provided to the crew by all system supports contributed to the risk of error due to in adequate information and resulted in a collision.

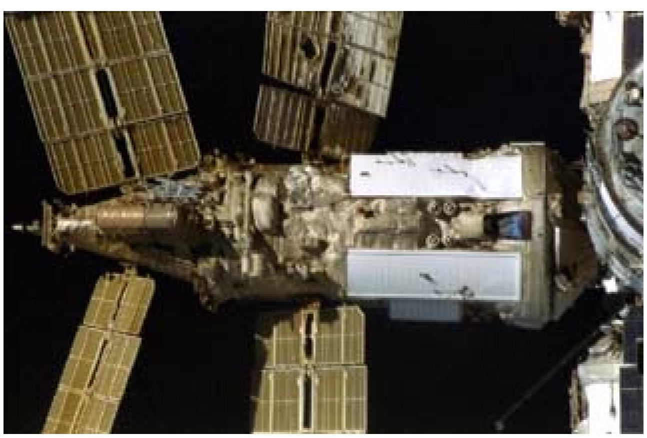

Figure 23-9. Photo of the damage incurred by the collision by the Progress 234 vehicle with the Mir space station. (Photo courtesy NASA[7])

Ground-Based Evidence

- *Example of Poor Arrangement of Control Area (Category III [24]).* In March 1987, 188 people were killed in the sinking of a ferry boat in Zeebrugge, Belgium. After unloading passengers at one port, the ferry backed away from the dock with the bow doors open. As a result, the ferry became swamped with water and finally sank. The responsible Assistant Boatswain had assumed other personnel had taken the responsibility of closing the bow doors, and took a break. Ultimate responsibility to check the worthiness of the ship belonged to the Captain who had positioned himself on the wing of the bridge to monitor backing out of the berth. Although that was the best vantage point for viewing the ship's stern, the location offered no direct view of the critical conditions at the bow of the ship. The control console was located some distance from that vantage point and was not immediately accessible. It would not have helped if they had been co-located, as there was no indicator of door status on the console. Error occurred due to the absence of needed informational cues at all vantage points and caused crew errors due to inadequate information.

2. Environment

Spaceflight Evidence

- *Example of Environmental Induced Engineering Failure (Category III [3, 25]).* On January 28, 1986 the Space Shuttle Challenger mission 51-L ended 73 seconds after launch. Space Shuttle Challenger exploded killing all 7 crewmembers on board (Figure 23-10). The disaster was caused by a failure in the aft field joint between the two lower segments of the right solid rocket motor. Hot gas passed by the .280 inch thick O-rings impinging on the external tanks causing it to disintegrate due to severe aerodynamic load. During the firing of the solid rocket motor the joint tang and clevis assembly expanded. Normally, the O-rings follow or track that expansion and prevent gases from escaping. However, on that day it was 15 degrees colder than any previous launch, it was exposed to 7 inches of rain, and ice probably formed preventing the O-ring from working properly and allowing the gas to destroy the structural integrity. Although the design proved to be too sensitive to too many factors and resulted in a complete system failure, the event might have been avoided had the decision makers been aware of the impacts the environmental conditions had on the O-rings, and the decision to launch that day could have changed. The event occurred because the decision makers did not have complete situational awareness of all contributing factors; the risk of error due to inadequate information could have been avoided.

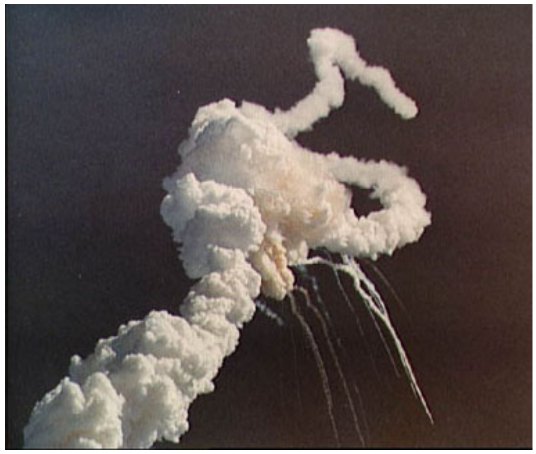

Figure 23-10. The photo depicts the Space Shuttle Challenger explosion.
(Photo courtesy of the U.S. Centennial of Flight Commission[20])

Ground-Based Evidence

- *Example of Inadequate Control Room Design (Category III [21, 26]).* The chemical accident that occurred on December 4, 1984 in Bhopal, India, initially resulted in the deaths of approximately 3800 people and injured more than 200,00. However since then, the number of deaths has increased to approximately 25,000, at a rate of approximately 700 people per year. The overall design and safety of the plant's control room had many inherent human-centered design problems. Many of the operator displays provided inaccurate information. Many of the displays were broken, malfunctioning, off-scale, or were considered to be unreliable. All of these issues contributed to the operators' inability to properly monitor the status of the plant's operations. Without displays that provided necessary status information, operators were not aware of the problems occurring within the plant until it was too late to enact the appropriate safety procedures. Thus the fatal event occurred because of an error that occurred due to inadequate information.

3. Stowage

Spaceflight Evidence

- *Example of Deficiencies of Sims and Mockups in 1-G (Category III [5]).* Given the challenges with representing a true 0-g environment on the ground, simulated environments and full-scale models (Sims and Mockups) have not been completely representative of flight conditions on the ISS, in terms of stowage (Figure 23-11). On-orbit there is the benefit of weightlessness which allows items to be stored on any axis with proper restraints. The crew can "float" through the volume and position their bodies to move around obstructions or protrusions in the translation paths. However, in 1-g you are limited to how you can stow items because gravity affects how humans operate in the mock-ups. Options are restrictive and it's not possible or safe to place things where they would be stowed on ISS, given the 1-g constraints of a "floor" based translation path. Because the Sims and Mock-ups aren't completely representative of 0-g conditions in all cases, the crew experiences learning curve once on-board. It's often difficult for them to find items and operate nominally upon arrival at ISS, resulting in errors, based on a disconnect between the ground training and actual life on orbit, essentially inadequate information.

Figure 23-11. These two photos are of Johnson Space Center mock-ups of the Crew Exploration Vehicle and the Space Shuttle trainer. (Photos courtesy NASA[7])

Ground-Based Evidence

- *Example of Poor Accessibility and Awareness of Stowed Emergency Equipment (Category IV [27]).* On September 6, 2005, the flight crew of a Sikorsky S-76A helicopter executed a forced ditching into the open waters of the Gulf of Mexico following an in-flight fire and eventual dual-engine power loss. Both flight crewmembers and three of the 10 passengers sustained serious injuries; seven passengers sustained minor injuries.

  As the helicopter hit the water, the floats on the right side burst, causing the helicopter to roll sharply to the right. The occupants quickly evacuated the rapidly flooding cabin. Neither of the two 18-pound life rafts stored under the outboard first row of cabin seats were retrieved before the helicopter sank. The captain stated, during a post-accident interview, that he thought about retrieving one of the life rafts, but was unable to locate them. The first officer stated that there was not sufficient time to remove the life rafts, because the helicopter sank so rapidly. Without a life raft to protect them from the Gulf waters, several of the passengers suffered hypothermia.

  Poor information and stowage practices contributed to the fact that the passengers were not aware of the location or how to access the life boats and committed the error.

4. Human Computer Interaction

Spaceflight Evidence

- *Example of Usability Issues with ISS Displays (Category III [5]).*

  The technology on-board the ISS has historically lagged behind available ground-based technologies (Figure 23-12). Displays and software platforms are different from application to application depending on the task that is being supported. Many interfaces on board are not the same as those commonly used on Earth. This has been a source of operational frustration for the crew. Therefore, it is important to provide crews with systems that are similar to those used on the ground to avoid impacts to human and system efficiency and performance.

  Usability issues have occurred associated with the use of displays that do not share a common overall infrastructure and layout to promote ease of use and understanding of intended operations. The ISS crew has lost time trying to understand to the use of each display, and have committed several errors using the displays, e.g., incorrect data entry, navigational errors, or inaccurate interpretation of the data within the displays. When every display is different and has to be independently trained and mastered, the operator is at risk of committing an error, especially in the event of an emergency. This can be attributed to reverting to an uncomplimentary skill base from another display design due to the poor human-centered design of the first display. This natural human tendency may override training and cause the human to make an error due to inadequate information.

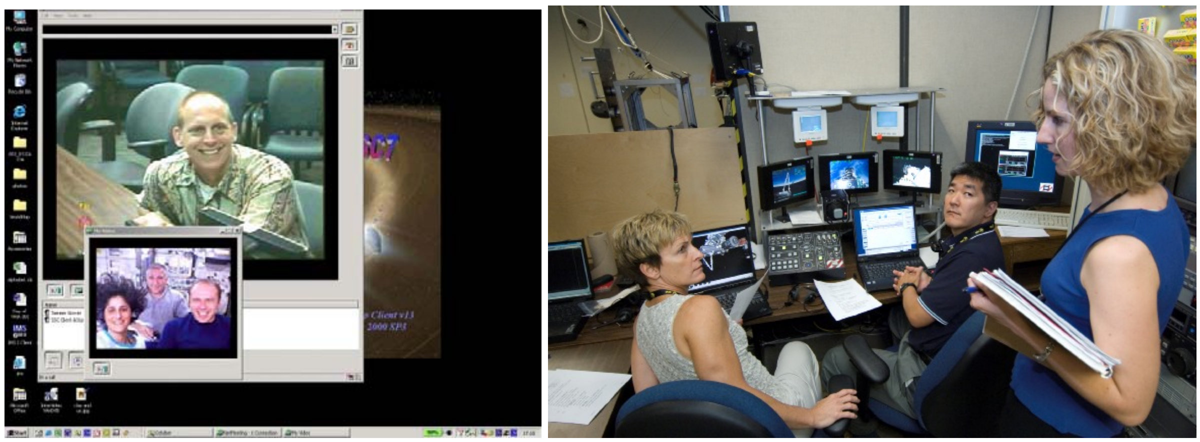

Figure 23-12. The photos illustrate crew displays and training on crew displays for ISS (Photos courtesy NASA[7])

Ground-Based Evidence

- *Example of Inadequate Displays and Controls (Category III [21, 28]).*

The March 28, 1979 Three Mile Island nuclear power plant accident provides an example of how inadequate information nearly resulted in a nuclear disaster by causing a human error. Many of the controls and display system lights were poorly designed so that 1) the information necessary for operating the power plant was difficult to find, and 2) the controls and lights conveyed either incorrect information or confusing information to the user. Examples of design issues included: controls located far from instrument displays that showed the condition of the system; cumbersome and inconsistent instruments that often looked identical and were placed side-by-side, but controlled widely differing functions; instrument readings that were difficult to read, obscured by glare, poor lighting or actually hidden from the operators (many key indicators were located on the back wall of the control room and many of these indicators were faulty or misleading); contradictory systems of lights, levers or knobs (e.g., lever up may have closed one valve, while pulling another lever down may have closed another). Had correct and adequate information been provided, the error may not have occurred.

5. Hardware and Tool Design and Maintenance

Spaceflight Evidence

- *Example of Limited Communication Capabilities (Category III [9]).*

The ability of the crew to hear voice communication with ground personnel is sometimes degraded, costing the crew extra time to clarify issues and repeat things. Communication across ISS modules is also difficult due to the ambient noise levels. The current ISS communication system consists of audio terminal units (ATUs) located at each end of the ISS modules (Figure 23-13). The crew must translate to the ATUs in order to talk to the ground or between ISS modules. An estimated 6 hours/week of crew time is spent translating to an ATU for communication.

During drills and caution and warning alarm events, the crew has reported having difficulty contacting ground personnel prior to acknowledging caution and warning alarms, because the communication system becomes disabled (inadvertently) during the caution and warning event. Re-establishing communication with the ground can take up to 30 minutes. In the event of an emergency, these communication barriers to quick and accurate communication and information can contribute to costly human errors, and can pose a threat to the crew returning the vehicle and mission to a safe condition.

Figure 23-13. The photos depict crewmembers using the audio terminal units to communicate. (Photos courtesy NASA[7])

Ground-Based Evidence

- *Example of Lack of Redundant Systems Deficiencies (Category IV [29, 30]).*

"About 4:38 p.m. central daylight time on October 12, 2003, westbound Northeast Illinois Regional Commuter Railroad (Metra) train 519 derailed its two locomotives and five passenger cars as it traversed a crossover from Track 1 to Track 2 near Control Point 48th Street in Chicago, Illinois. The train derailed at a recorded speed of about 68 mph. The maximum authorized speed through the crossover was 10 mph. There were approximately 375 passengers and a crew of 3 onboard. As a result of the accident, 47 passengers were transported to eight local hospitals. Of these, 44 were treated and released, and 3 were admitted for observation. Damages from the accident exceeded $5 million."

It was determined that the probable cause of the derailment of Northeast Illinois Regional Commuter Railroad (Metra) Train 519 was the locomotive engineer's loss of situational awareness minutes before the derailment, primarily, because of his preoccupation with certain aspects of train operations that led to his failure to observe and comply with signal indications. Contributing to the accident was the lack of a positive train control (PTC) system at the accident location. Positive Train Control (PTC) technology is capable of preventing over-speed derailments, train-to-train collisions, and casualties or injuries to roadway workers.

The operator of the train should have been able to receive an alert message no matter where they were or what they were doing in the train. Multiple methods should have been employed to audibly and visually convey needed information to the operator to prevent the error that result in an accident.

6. Procedures and Training

Spaceflight Evidence

- *Example of Poor Information Conveyance Methods (Category III [5, 9]).*

Electronic procedures have been difficult to use on the ISS. Frequently, the crew has had to spend time navigating between various menus because the procedures were difficult and lengthy. In many cases the content of the procedures has contributed to inadvertent procedure step-skipping and poor task execution. Many of the electronic updates have had to be printed out to update procedural books, costing the crew time with printing and changing out procedure pages. Printing is difficult on orbit; therefore, it is not optimal to send up long electronic procedures. With too much information within a given set of procedures and not enough time to complete the task the crew has been in unsafe situations, because the information they need to do the task safely was not presented to them in a usable format for the task at hand, causing errors (Figure 23-14).

Figure 23-14. This photo illustrates a crewmember using an electronic ISS procedure printout to conduct a task. (Photo courtesy NASA[7])

Ground-Based Evidence

- *Example of Inadequate Procedures and Training (Category IV [31]).*

"On the morning of April 7, 2000, the Piney Point Oil Pipeline system, which was owned by the Potomac Electric Power Company, experienced a pipe failure at the Chalk Point

Generating Station in southeastern Prince George's County, Maryland. The release was not discovered and addressed by the contract operating company, Support Terminal Services, Inc., until the late afternoon. Approximately 140,400 gallons of fuel oil were released into the surrounding wetlands and Swanson Creek and, subsequently, the Patuxent River as a result of the accident. No injuries were caused by the accident, which cost approximately $71 million for environmental response and clean-up operations. It was determined that the probable cause of the accident, was at the generating station there was a fracture in a buckle in the pipe that was undiscovered because the data from an in-line inspection tool was interpreted inaccurately as representing a T-piece. Contributing to the magnitude of the fuel oil release were inadequate operating procedures and practices for monitoring the flow of fuel oil through the pipeline to ensure timely leak detection and conveyance of that information to the human" to reduce the risk of error.

D. Risk Associated with Poor Task Design

The body of evidence that exists from spaceflight data indicates that poor task design has compromised mission safety and effectiveness and continues to pose risks for future spaceflight. Ground based evidence demonstrates that poorly designed tasks and methods and provisions to perform these tasks has caused and contributed to catastrophic (or potentially catastrophic) accidents. Extensive data from highly technological fields including aviation, armed forces, ground transportation, and power illustrates errors due to poor task design and subsequent operator error or incidents remain areas for concern regarding risk to the human operator and missions.

1. Architecture and Topology

Spaceflight Evidence

- *Example of Poor Accessibility (Category III [3])*

  In the late 1980's the Magellan spacecraft power control unit arrived at the Kennedy Space Center for Space Shuttle launch preparations. The Magellan unit was connected, and an extensive electrical power check was needed to ensure it was operating properly before applying power to the Shuttle subsystems. A technician proceeded to make a blind-mate of an electrical harness power cable to the Magellan. As the connection was buried deep in the space craft, it was visually out of the view of the technician. Because the technician couldn't see the connection it was impossible to verify that the mate had been made correctly. As a result, the mate was not correct and sparks and flames erupted from the cable connection operation. The fire caused damage to the battery, connector and thermal blanket to the Magellan spacecraft. Had the task been designed to fit the operator and required action, the risk due to poor task design would have been reduced.

Ground-Based Evidence

- *Example of Stowage Impacts to Architecture and Layout (Category III [32]).*

  On April 16, 1947 an enormous explosion occurred that was one of the worst industrial disasters in the U.S. A French Liberty ship, GrandCamp, was loaded with sisal twine, peanuts, drilling equipment, tobacco, cotton and a few cases of small ammunition and 2,341 tons of ammonium nitrate. No particular safety precautions were in place to prevent or correctly react to emergency situations. Approximately 15 minutes after the cargo began to be loaded, smoke was noticed coming out of one of the cargo hatches. In order to protect cargo contents, water was not initially used on the fire and steam was used to it. With the introduction of steam, the ammonium nitrate changed state to water vapor and nitrous oxide, and produced a chemical reaction with more heat.

The GrandCamp exploded at 9:12 a.m. along with two other vessels. As a result, at least 581 people died, 5,000 were injured, 500 homes were destroyed, 1,100 vehicles were damaged, 362 freight cars obliterated, 2000 left homeless. Property damage was estimated in excess of $700 million (today's dollar value), with $500 million in petroleum losses.

From an architecture and stowage layout perspective, additional provisions could have been made to increase safety and improve actions taken to respond in similar situations. According to the Fire Prevention and Engineering Bureau of Texas Dallas, Texas; The National Board of Fire Underwriters, (1947) storage and handling of hazardous materials, such as ammonium nitrate, should follow multiple procedures including stowing explosive or hazardous materials in masonry or fireproof sprinkler equipped buildings on skids or pallets on concrete floors with a minimum one foot clearance from building walls. Clearly-designated and architecturally-optimized stowage areas can impact crew task performance efficiency regardless of what type of cargo is being transported whether on the ground, on the sea or in space.

2. Environment

Spaceflight Evidence

- *Example of Fungal Growth (Category III [5]).*

The living volume of the ISS Russian Service Module is designed for day-to-day tasks such as food preparation and consumption, waste and hygiene activities, and exercise. During the design process, the implications of material choices were not fully evaluated. The scope of activities and tasks to be conducted within the Service Module weren't completely understood with respect to the types of materials that would be needed to prevent fungal/bacterial growth and provide for ease of maintenance. The Service Module walls were covered with a Velcro-type material to assist with easy attachment and storage of items. What wasn't considered was the effect the nominal operations would have on the materials chosen and how this choice would affect the habitability of the crew. The material, somewhat like carpet, became a breeding ground for fungal/bacterial growth due to the presence of liquid from food preparation, food residues, and human metabolic waste and by-products due to exercise and hygiene activities. The material absorbed these liquids over time, and has created spots of fungal/bacterial growth necessitating replacement of the affected surfaces. Poor facility design directly contributed to an occurrence of an overall poorly designed task environment.

Ground-Based Evidence

- *Example of Mode Confusion (Category III [33]).*

"August 31, 1983, Korean Air Lines Boeing 747: Two minutes and ten seconds after take-off from Anchorage, Alaska, crew engaged the autopilot in HEADING mode. Due to a difference between true and magnetic north at this latitude, the resulting flight path to Seoul, Korea deviated into sensitive Soviet airspace. Four MiG-23 fighters were scrambled to intercept the airliner, but were unable to reach it before running low on fuel and returning to base.

As the airliner approached Sakhalm Island, two Soviet Su-15 fighters on night alert scrambled to intercept, with orders that the intruder was a combat target. Due to the darkness, the intercepting fighter could not ID the airliner; confused communications with the fighter pilot and ground control led to the erroneous conclusion that the airliner was an American RC-135. This led to the Soviets hailing the airliner on an emergency/distress frequency, which the KAL crew was not monitoring. The Soviet air-defense commander ordered the fighter pilot to flash his lights and fire a burst of 200 bullets to the side of the airliner. At nearly the same time, the KAL crew received clearance to climb from 33,000 to 35,000 feet, and was unaware of the Soviet "warning shots." The airliner's ascent was misinterpreted as an evasive maneuver; the fighter pilot was ordered to engage afterburners and destroy the target. The fighter pilot launched two air-to-air missiles, destroying the B-747 and killing all 269 souls onboard." Due to miscommunication and environmental conditions that contributed to the flight, the ultimate design of the task with the airliner caused all lives to be in danger and lost.

3. Stowage

Spaceflight Evidence

- *Example of Inadequate Stowage Tracking System/Methodology (Category III [9]).*

The tracking methodology for items stowed on ISS has not been consistent with every Expedition. Items have not been stowed adjacent to each other based on their functional use, causing crewmembers to search at opposite ends of the ISS for equipment needed for particular tasks. The Inventory Management System (IMS) on ISS has not been used consistently to track items to be stowed, and not all items have been tracked (Figure 23-15). When items were moved they were not placed back in their designated area and the IMS has not always been updated to reflect the new location. This caused the crew to spend time searching for items they needed for daily tasks and contributed to a poor task structure in terms of how things are stowed and collected. The International Partners (IP) have been inconsistent in how they track equipment and supplies in the ISS IP segments and they tend to be less accurate than the U.S. Inefficient task design practices have lead to a loss of crew time, increased frustration and potentially unsafe nominal operating conditions.

Figure 23-15. These photos depict a crewmember managing stowage and an over abundance of stowage in the translation paths of the FGB on ISS (Photos courtesy NASA[7])

Ground-Based Evidence

- *Example of Impacts due to Stowage and Crew Provisioning (Category III [34, 35]).*

Damage control tasks that sailors aboard US Navy vessels are required to perform can put them in grave danger at a moment's notice. The terrorist attack on the USS Cole on October 12, 2000 is one example of these dangerous situations. While refueling in Aden Harbor, Yemen, the USS COLE was attacked by a small boat carrying explosives. The explosion created a 40 by 60 foot hole in the destroyer and killed 17 sailors.

Many lessons learned from the USS Cole tragedy were assessed and applied to US Navy damage control processes to improve overall safety and damage control task design. The US Navy's Damage Control, Fire Protection Engineering and Chemical, Biological and Radiological Defense (CBR-D) website indicated one specific lesson learned was related to post -re overhaul and clean up tasks. Prior to the USS Cole attack and during the overhaul for the USS Cole attack, damage control personnel were only provided a single pair of gloves to protect their hands while conducting post fire debris clean up tasks. While performing these tasks, the gloves quickly became covered in flammable materials and dangerous to the crew and were useless for continued firefighting or damage control operations. The lack of consideration for necessary crew provisioning items and optimal stowage methods for these items put the USS Cole damage control personnel at risk while performing these critical tasks. If personnel had been provided with additional gloves to complete their tasks and a stowage method that would allow for rapid donning and doffing as the gloves became contaminated, overhaul tasks for the USS Cole could have been completed in a safer and more effective manner with effective task design.

4. Human Computer Interaction

Spaceflight Evidence

- *Example of Usability Issues with Cursor Control Devices (Category II [36]).*

  Future human exploration vehicles, including habitats, will be highly dependent on computerized, automated systems, necessitating an accurate method of interaction with computers. The design of any cursor control device will have to take into consideration a number of factors, including g-forces, vibration, gloved operations, and performance based on task specificity. Previous research has illustrated the need for additional development of cursor control devices within a spaceflight environment. Participants in eight flight studies (both parabolic and spaceflight) performed structured cursor control studies involving pointing, clicking and dragging of onscreen objects of various sizes.[37] The cursor control devices included mouse devices and trackballs. The general findings from these studies are illustrated below:

  - **KC-135** (multiple flights) and **STS-29:** Mechanical mouse did not function in microgravity – ball floats up, impeding roll. Two-inch trackball switch pressures excessive; restraint rails helpful. Optical mouse fastest and most accurate of devices tested.
  - **STS-29**: 2 inch trackball had too much "play" in the ball mechanism; restraint rails on the device were helpful. The optical mouse required too many pieces (work surface, pad, and mouse) and did not serve as a restraint.
  - **STS-41** This study used an updated trackball still had too much "play". Pen device was too error prone.
  - **STS-43:** 1 ¼ inch built-in laptop trackball had little or no "play" and it worked well: it was the most desirable, the fastest, and the most accurate.

Based on the issues identified from the aforementioned research, a study was conducted to identify the necessary characteristics of a cursor control device for future space mission environments. Data regarding timing and error data was collected on several commercial and proprietary cursor control devices in both gloved and un-gloved conditions. The selected devices included a roll bar device, four different trackball devices, a track pad mouse, two optical air mouse devices, and a joystick. For both the gloved and un-gloved conditions, the results indicated that overall the track ball devices performed better (with regard to accuracy and timing) than the other devices and, different devices were preferred for different tasks. This illustrates how important task design is in dictating the support items that will be needed to achieve operational efficiency.

Ground-Based Evidence

- *Example of Poor Task Structure / Mode Confusion (Category III [38])*

  "January 21, 1985, Galaxy Airlines Electra II airliner: Distracted by an interruption, Reno Airport ground crew failed to fully secure an air-start equipment door on the airliner wing. There was no indication or feedback to the crew that the door was not secure, per their nominal task execution. The door came loose and caused severe buffeting in flight, from disruption of airflow over wing. Unaware of the true cause, pilots believed the aircraft was in structural danger and requested return to airport. On approach, pilots reduced engine power and the aircraft crashed when the airspeed dropped too low. Seventy deaths resulted due to no system feedback to the operator. Due to the poor system (the lack in the system information regarding the pending risk) and task design, operator error occurred.

5. Hardware and Tool Design Maintenance

Spaceflight Evidence

- *Example of Excessive Maintenance Tools (Category III [9])*

Maintainability of systems on a long-duration orbiting vehicle such as ISS is critical. Most hardware, particularly on the U.S. segment, requires frequent maintenance and many tools. The ISS tool kit has improved greatly since early Expeditions, but the quantity of tools is excessive for a microgravity environment. This situation is a significant impact to crew time, particularly when the need for frequent maintenance is coupled with the limited accessibility of items on-orbit (Figure 23-16).

The design of utility equipment, such as connectors and latches, has not been standardized, which can cause crew confusion when operating the hardware. Equipment intended to be relocated on-orbit needs to be designed with ease of relocation in mind. For example, the handrails were designed to be moveable but early ISS crews found their attachment mechanism somewhat difficult to use. Poorly designed tasks were a result of the perspective that systems wouldn't need to be maintainable because they were reliable. However many system failures and reliability issues have been experienced and the task designs have contributed to unsafe accessibility issues for the crew.

Figure 23-16. These photos depict crewmembers conducting maintenance activities with tools and in hard to access areas on the ISS. (Photos courtesy NASA[7])

Ground-Based Evidence

- *Example of Poor Task Design for Use of Hardware; (Category III [39, 40]).*

Adamski & Westrum contend that software design may be simpler than designing hardware for cognitive tasks, especially those that involve controlling technology such as weapons.[39] Previous disasters and failures have demonstrated that cognitive tasks intended to control volatile technology may be more complicated than some may expect, despite proper training or task allocations. Oversights and mistakes can still be made.

On July 29, 1967, in the Gulf of Tonkin, a massive fire killed 134 and injured 62 of the 5,000 officers and enlisted crew onboard the USS Forrestal. The incident was caused by the premature launch of an air-to-ground rocket from an A-4 Skyhawk aircraft waiting to eventually take off from the deck of the aircraft carrier. Adamski & Westrum indicated that investigations revealed the task of arming the rocket had not been performed correctly, nor by crewmembers that had been trained to perform the task or work with the weapons hardware.[39] Prior to the incident, it had been assumed that the crewmembers that performed the task knew the proper steps to prepare the live rockets, but this was not the case. By permitting untrained individuals that were not prepared to perform these types of cognitive tasks with live weapons hardware, and by not assigning the trained crewmember to interface with the weapons hardware, lives were lost. It was ultimately the poorly designed task, utilizing inappropriate resources that caused the human error to occur.

6. Procedures and Training

Spaceflight Evidence

- *Example of Poor Hazard Conveyance for Tasks (Category I [41]).*

  The primary purpose for using caution and warning (C&W) advisory blocks within procedures is to protect the crew and the hardware from potentially unsafe conditions or incidents. There have been a number of complaints from the ISS crew concerning the implementation and overabundance of cautions and warnings within procedures (Figure 23-17). The excessive use of cautions and warnings within procedures has contributed to the desensitization of the crew to cautions and warnings (e.g., accidental procedure step skipping and inattention to important caution and warnings because they are embedded in trivial warnings). A review of the procedures was conducted to identify root causes which included:

  - Lack of consistency in how procedures were written:
    - There is more than one document that provides caution and warning writing standards, which introduced inconsistency between standards, Operations Data File Standards SSP 50253 and memo DO12-96-27 Implementation Plan for Operation Controls of ISS System Hazards.
    - Lack of consistency with interpreting the standards between procedure writers.
    - Cautions and warnings were not clearly defined and accurately used in the examples in the standards documents.
    - There were multiple procedure writers and multiple reviewers, which introduces inconsistencies in the final procedure.
  - Cautions and warnings were used incorrectly throughout almost all procedures that were reviewed:
    - Cautions and warnings were not located in the correct place within procedures.
    - Some cautions and warnings within procedures had been identified as procedure steps rather than cautions and warnings.
    - Sometimes a caution was used when it should have been a warning and vice versa.
  - Cautions and warnings were used generically for any danger category and there is no way to understand degree of caution or warning criticality. It was not clear in some cautions and warnings what the hazard actually was.

The method in which the information was chosen to be conveyed, and the way the tasks were design around the procedures, led to the occurrence of errors while using the procedures.

Figure 23-17. These photos illustrate crewmembers using procedure checklists and training procedures to complete tasks. (Photos courtesy NASA[7])

Ground-Based Evidence

- *Example of Inadequate Procedures (Category IV [42]).* On January 8, 2003, Air Midwest flight 5481crashed shortly after takeoff at Charlotte-Douglas International Airport. The 2 flight crewmembers and 19 passengers aboard the airplane were killed, 1 person on the ground received minor injuries, and the airplane was destroyed by impact forces and a post crash fire.

  Flight 5481 was a regularly-scheduled passenger flight to Greenville-Spartanburg International Airport. The cause of this accident was the aircraft's loss of pitch control during takeoff, which resulted from the incorrect rigging of the elevator control system compounded by the airplane's center of gravity, which was substantially aft of the certified aft limit. Evidence revealed that the aircraft underwent a D6 maintenance check at Air Midwest's Huntington Tri-State Airport (HTS) maintenance station the day prior to the accident. The quality assurance (QA) inspector on duty the night of aircraft maintenance check was providing on-the-job training to two mechanics on specific tasks associated with the D6 maintenance check. Neither mechanic had previously performed the complete D6 check. One of the mechanics was in charge of adjusting cable tension on the aircraft and used the elevator control system rigging procedure as a guide to perform the task. The procedure did not isolate the adjustment of cables, so the mechanic chose to bypass several steps that he and the QA inspector deemed to be irrelevant. One of the steps bypassed was critical to properly adjust the cables in aircraft equipped with an F-1000 FDR as this aircraft did. By not performing this step it was not possible for the elevator control system to be rigged correctly after adjusting the cables. Based on the task and procedure design, the maintenance workers were not aware that certain steps were critical and couldn't be skipped, thus causing the workers to commit an error during their check-out of the equipment.

V. Computer-Based Simulation Information

One of the difficulties associated with developing human habitats for remote environments and interfaces for complex systems is anticipating all of the operations that may be required. This is further complicated by the ability to identify all the needs of the users to successfully complete the operations, there is often many unknowns. It is critical to have an understanding of how the human will integrate into a system, to identify risk that may be inherent in a concept or a design. Therefore modeling is used to simulate remote habitats and to evaluate design concepts for impacts to the human. All in an effort to reduce the risks associated with reduced safety and efficiency due to poor human factors design, error due to inadequate information, and with poor task design. Currently we use a suite of human modeling products to detect potential risks to the human associated with the three SHFE risks, long duration spaceflight modeling includes the following examples.

A. Risk of Reduced Safety and Efficiency Due to Poor Human Factors Design

Example of Automation and Human Safety (Category II [43])

In the 1990's NASA and the FAA engaged in several research efforts with the goal of providing safer, faster, and more fuel efficient routing operation in flight management through the use of automation in air traffic control aiding. By integrating automation technologies into the system it was thought that optimized routing, sequencing, and scheduling in terminal areas could be achieved while relaxing constraints in the en-route environments to accommodate user-preferred routing and schedules. Man Machine Integration Design and Analysis System (MIDAS) was adapted to model a predictive flight crew performance. This particular model specifically focused on predicting the performance of a two pilot flight crew when responding to information generated by an automated air traffic control system, Center TRACON Automation System (CTAS).

During the course of the research the experimenters conducted two computer simulations. The first simulation employed a model of top of descent (TOD). This model was developed with the goal of determining an optimal range of time for the issuance of CTAS decent clearance so that the aircrew would be likely to accept the clearance and enact it using flight deck automation (rather than manually commanding the descent). The model confirmed that as the TOD point drew the closer the aircrew will select the less automated alternative mode of control. As the aircraft approaches within 5 to 8 miles from the CTAS required TOD point, the number of successes in any clearance compliance is reduced significantly.

B. Risk of Error Due to Inadequate Information

Example of the Cockpit Avionics Upgrade (CAU) Evaluation (Category II [44])

Inefficient or inadequate presentation of information presents a risk to crew effectiveness and safety, especially during off-nominal operations. In 1999, NASA Johnson Space Center initiated the process of upgrading the cockpits of the Space Shuttles. The primary impetus for the upgrade was the perceived risk of reduced safety and efficiency of shuttle operations due to the lack of a human-centered design approach to information conveyance of the 1970's-era display formats. The product of the CAU effort was a new suite of explicitly task-oriented display formats that

- o consolidated and integrated task-related information;
- o more clearly supported fault detection, isolation, and recovery operations;
- o used color-coding to guide and manage operators' attention;
- o streamlined display navigation with new display control devices.

As part of the CAU project, a thorough human-in-the-loop evaluation of the CAU display formats in JSC's shuttle mission simulator (SMS) was conducted, which directly measured operational efficiency and error rate in a series of full-mission simulations of off-nominal ascent and entry scenarios. The scenarios were completed with both the current display suite and cockpit interface devices as well as with the upgraded displays and interfaces. The results provided an empirical database quantifying the performance benefits and enhanced operational efficiency that accompanied the human-centered redesigns. When asked about conditions during their just-completed scenarios, crewmembers answered close to 75% correctly in the CAU cockpit; that figure was typically less than 40% in the current cockpit. Workload was rated 38% lower with the CAU cockpit. The incidence of a particularly safety-critical form of operator error (e.g., the percentage of systems malfunctions and flight anomalies that went unrecognized) stood at 30% in the existing cockpit; however, in the CAU cockpit the rate of error was only 10%– a 67% reduction.

Finally, while there was little difference between the current and CAU cockpits when diagnosing the easiest malfunctions, there was a distinct latency advance for the CAU cockpit for the more difficult malfunctions. In the very slowest (most difficult) cases, the average CAU advantage was 40 seconds. This demonstrates how improved display formats can reduce the risk of operation error due to inadequate information.

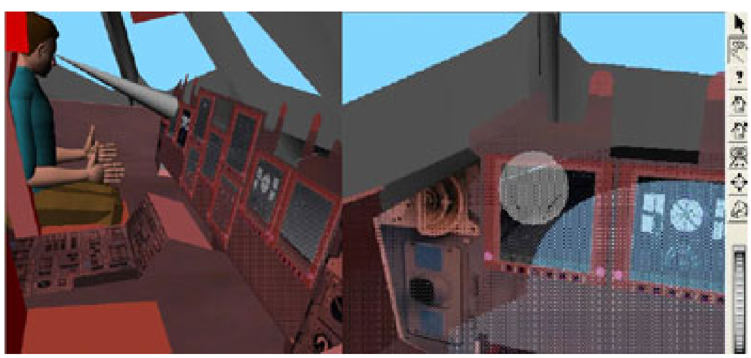

Figure 23-18. MIDAS simulations were conducted to reproducing the findings of the CAU display suite evaluation. Task timelines and workload outputs were examined as part of these simulations." (Photo courtesy NASA/Ames Research Center)

Figure 23-19. Implementation of glass cockpit panels afforded designers the option of upgrading Shuttle display formats. (Photo courtesy NASA[7])

C. Risk Associated with Poor Task Design

Example of a Poor Maintenance Task Design (Category III [45])

During evaluation and identification for locations to place the second treadmill in the ISS to support a crew of 6, the BHMS modeling software identified risks to the ability to perform installation of the treadmill based on the temporary location. The planned location would be co-located with the Crew Quarters in Node 2; accessibility was identified as a problem based on the configuration of the Crew Quarters bump-outs which extended into the translation paths and the access area for the planned second treadmill. The BHMS modeling software was successfully used to identify accessibility issues and a non-compliance with Space Station Requirements for accessibility. NASA was able to establish that the planned tool would not allow the crew to conduct the installation task successfully and new tool options would need to be pursued to reduce the risk associated with the poor task design.

VI. Risk in Context of Exploration Mission Operational Scenarios

When examining risks associated with a lack of human centered design for future exploration, specifically the Lunar Outpost and Mars missions, it is important to remember that the Lunar missions will add a substantial set of independent lessons learned, experiences and more definitive gaps that will apply to Mars exploration. These will be better addressed during the Lunar Outpost phase of exploration. For the purposes of this evidence report, specific focus is paid to how the risks present themselves for the Lunar Outposts and how these risks will transfer forward for Mars exploration with respect to architecture and topology, environment, stowage, human computer interaction, hardware and tool design and maintenance, and procedures and training.

Future exploration missions may last as long as three years. During this extended timeframe, crews will face the challenges of physical de-conditioning, prolonged isolation and confinement, significant communication delays with ground support, multiple changes in environmental stressors, and increased responsibility and autonomy. Utilizing good human-centered design techniques for missions, vehicles, and habitats is a significant tool for the management and control of risk of reduced safety and efficiency due to poor human factors design, risk of error due to inadequate information, and risk associated with poor task design. Without human centered design poorly designed tasks and procedures, hardware and systems, habitats and environment, lack of task analysis and understanding of operations, disregard for human-in-human machine system, lack of integrated system design approach, and lack of user evaluations and iterative design capture are all much more likely to occur.

A. Risk of Reduced Safety and Efficiency Due to Poor Human Factors Design

There will be significant challenges associated with the Lunar Outpost and Mars missions in terms of risks of reduced safety and efficiency due to poor human factors design to the crew. The extended length of missions and new physical challenges of a partial-g environment increase the criticality of good human centered design, including:

Where **architecture and topology** are concerned, anthropometric considerations will be different from a 0-G environment, no longer will the crewmember be able to adapt and navigate as easily around a poorly designed habitat or obstructions in the translation path.

The **environment** will introduce new risks associated with different types of air quality issues, Lunar or Mars dust, radiation exposure scenarios and unique lighting considerations (e.g., increased shadowing on the surface of the Moon and being further from reflective light from the Sun).

Stowage capabilities will need to address the risk of not having appropriate supplies or spares available and accessible in a timely manner and increased volume to store many spares will be a consideration to insure crew safe operations.

With increasingly complex task demands placed on the human, **human computer interaction** will be of paramount importance to protect for the safety and efficiency of the crew and the mission. The computer displays and controls systems will need to be more complex in capability, but not in operation.

Hardware and tool designs will have to be much more reliable to reduce maintenance and repairs needed, and complex interfaces minimized and more commonality designed into each operating system. Without intuitive computer interface systems and hardware designs, the crew will be less able to operate optimally and safely while trying to maintain a semi to fully autonomous state during Lunar Outpost or Mars missions.

In addition, without intuitive designs, more complex **procedures** and longer **training** protocols would be required leading to an increase in workload and stress.

Attention paid to good human-centered design practices will help ensure that there is a good match between crew capabilities during mission operations and the tasks that they are asked to perform, as well as the equipment used to perform the task and ultimately protect the crew's safety.

B. Risk of Error Due to Inadequate Information

With more complex information and mission requirements for the Lunar Outpost and Mars exploration, the reliance on technological supports for multiple types of information communication methods will be needed. Based on architectural and topological design these systems will become more complicated. Additional supports will be needed to accommodate the hardware and systems. The risk to the human that an error in information processing or task execution will occur becomes greater due to increased cognitive demands and potentially incompatible information conveyed.

The hardware and systems will need to be "smarter" in terms of accurately communicating the state of the internal and external living and working environment to the crew. There will be much more reliance on good **architecture and topological** layout of the systems within the habitable volume.

In the event that the crew faces failure events, whether **environmentally** or otherwise induced, they will need to be immediately, accurately and clearly informed.

A **stowage** system will need to be in place that makes all aspects of the living environment intuitive. This includes a system of labeling and inventory management that clearly conveys what and where items are located, and how many of the items exist. This will be critical when communication lags and re-supply events occur less frequently or not at all. Emergency situations could be exacerbated without knowing all the pertinent information, i.e. not being aware medical supplies were low and re-supply was needed but not requested or supplies weren't utilized with regard to inventory counts.

Display and controls systems will have to be designed such that their increased complexity, based on Lunar Outpost and Mars mission, does not interfere with the conveyance of needed information, while affording easy **human computer interaction**. If displays and controls are not intuitive and the right information and interaction enforced by a good human centered design, safety incidents could result.

Increasingly compact hardware and systems will place greater demands on the crew in terms of accessibility and maintenance. **Hardware and tool design and maintenance** will be more difficult, and complex systems may necessitate additional tools that are complicated to use. The designs will need to maximize human capabilities and be designed to be easily used and maintained for the crew so that operation of the item is implicit or conveyed by design.

The more intricate the hardware and system designs are the more critical and complex **procedures and training** will be. The more detail we place into procedures and training, the more risk there is for miscommunication of information and decreased safety of the crew in an already complex and stressful environment due to inadequate modes of information communication.

C. Risk Associated with Poor Task Design

The task designs associated with Lunar Outpost and Mars exploration missions will be increasingly more difficult in terms of how mission tasks are designed around increased mission lengths and new operational environments and constraints.

With smaller vehicle spaces and new partial-gravity constraints the **architecture and topology** will have to change and will not be as accommodating to poor task design as a 0-g environment. With partial-gravity, adaptability of the human in terms of complicated and inefficient layouts will be reduced and uncomplimentary co-location of items will be exacerbated by new anthropometric concerns. Each activity center of the spacecraft or habitat will need to be configured to allow the crew to be efficient and productive.

The design of the vehicle and habitats will have to maximize all protections against new **environmental** concerns associated with the new elemental variables introduce by Lunar Outpost and Mars environments. The design will need to permit easy remedy of environmental emergencies and support a healthy day-to-day environment.

No longer will translation and habitability spaces be able to be used beyond capacity relying on the human to work around **stowage** infringement. With partial-gravity, the human will be less able to adapt to cramped workspaces and blocked translation paths. Without proper work and living space, task performance and mission success will be negatively impacted.

Tasks will need to be closely centered on automation supports with less need for crew and ground support. These tasks will need to be intuitive and almost automatic in providing good **human computer interaction** supports. However, capability for the human to intervene and easy error recovery must also be considered.

Attention will need to be paid to consistent and complimentary hardware and system designs throughout the Lunar Outpost and Mars missions to limit **hardware and tool design and maintenance** issues. Without consistent and common operating and environmental interfaces, the crew's productivity and ability to complete tasks will be hindered.

The more intuitive the operating interfaces are, the better the crew will be able to function without a heavy reliance on overly complex **procedures and training** paradigms. Intuitive operational interfaces will help simplify procedures and training references in general to support more human centered operations.

VII. Gaps

During 2006 and 2007, gap analyses were performed to identify human factors "research gaps" or knowledge needs. These analyses reviewed the current state of human factors topic areas and requirements to determine what data, processes or tools were needed to aid in planning and development of future exploration missions, and to assist in the prioritization of proposals for future research and technology development. These analyses included a review of space, space analog and human factors literature and the Life Sciences Crew Comments database, human factors experts and field user's interviews, and a full evaluation of the results. [2]

The lack of human centered design plays a role as a root cause in contributing to the three aforementioned SHFE risks. As illustrated in Figure 23-1, this lack of human centered design may be associated with multiple poor design considerations including, poorly designed tasks and procedures, poorly designed hardware/software, poorly designed habitats/environments, no task analysis/understanding of operations, disregard for human in human-machine system, lack of integrated system design approach, lack of user evaluations and iterative knowledge capture. The gaps described below can be directly attributed to these aspects of disregard for human centered-design and the SHFE risks.

Human-Centered Design

Gaps to be filled to allow effective implementation of human-centered design include, but are not limited to:

Poorly Designed Tasks and Procedures
An integrated understanding of the crew physical and cognitive constraints under actual mission conditions is needed.

Disregard for Human in Human-Machine System
Standardized human-centered design processes in NASA program and project management plans do not exist.

Lack of Integrated System Design Approach
Standardized processes to ensure design commonality across all human spaceflight vehicles and habitats are lacking.

Validated metrics for workload and usability for inclusion in the Spaceflight Human System Standards do not exist.

Spaceflight operational definitions of words used in the Spaceflight Human System Standards (e.g., acceptable, comfortable, other subjective terms) do not exist.

A. Risk of Reduced Safety and Efficiency Due to Poor Human Factors Design

Gaps to be filled to address the risk of reduced safety due to poor human factors design include, but are not limited to:

Poorly Designed Habitats/Environments
Tools and modeling capabilities to verify and validate acoustic noise level requirements during all design phases, do not exist.

Validated countermeasure technologies and strategies for manual and visual performance in high vibration environments do not exist.

No Task Analysis/Understanding of Operations
Guidelines for visual cues necessary for piloting future vehicles, the preferred methods for visualization and visual cue presentation and what visual cues can be simulated for the crew (as opposed to the use of out the window views), given the limited availability of windows do not exist.

Disregard for Human in Human-Machine System
The development of future spaceflight vehicles and systems must be focused on tolerating human vulnerability. An understanding of what kinds of errors occur and how they can be predicted, what are error-prone tasks, and how system robustness can be improved does not exist.

Disregard for Human in Human-Machine System & Lack of Integrated System Design Approach

A human-centered and system-safety approach for the operational paradigm for human factors does not exist.

Lack of Integrated System Design Approach

Systems to provide customized crew-system interaction (e.g., geographically appropriate alerting) and data from temporally asynchronous periods (e.g., the fault lag of malfunction signatures on a previous work shift) during quiescent phases of flight do not exist.

B. Risk of Error Due to Inadequate Information

Gaps to be filled to address the risk of error due to inadequate information include, but are not limited to:

Poorly Designed Tasks and Procedures

Objective measures for proficiency in crew medical training do not exist

The ability for the on-board crew to perform semi-autonomous planning and dynamic re-planning of schedules and tasks does not exist.

Validated guidelines for workload and usability do not exist.

Poorly Designed Hardware/Software

New display and control designs to meet the new environments of future spaceflight vehicle do not exist.

Adaptive cockpits to allow automated information display and crew-automation functional allocations in response to real-time assessment of crew condition, information processing activities, and current capabilities do not exist.

Display navigation and interaction concepts to accommodate the potential for oversized display formats do not exist.

Presentation methods for dynamic procedures displays based on the level of autonomy and the increase in available information do not exist.

Guidelines and display standards for information presentation on small displays, including head-mounted displays, do not exist.

Minimum size requirements (clearances) and location requirements for future vehicle displays and controls for personnel wearing space suits (both pressurized and un-pressurized) do not exist.

Guidelines are for workstation, controls, and display configurations to minimize ergonomic problems resulting from neuro-vestibular deconditioning do not exist.

Poorly Designed Habitats/Environments
Guidelines for the readability of displays and operability of controls during predicted high-vibration periods of operation do not exist.

No Task Analysis/Understanding of Operations
Flight crew and ground personnel functions and task allocations, based upon the expected increase in the level of autonomy for future missions, do not exist.

Human and automation mission function allocations based on increased levels of autonomy for future missions do not exist.

Guidelines for use of dynamic and adaptive automation based on increased levels of autonomy for future missions do not exist.

Disregard for Human in Human-Machine System
Incorporation of Human-Automation Interaction (HAI) into design and validation processes early in the design phase does not occur.

Lack of Integrated System Design Approach
Tools and techniques for the evaluation of human interaction with automated systems, (e.g., robotic systems, rovers, tele-operated systems, piloting systems, control, monitoring, and fault management systems, scheduling and planning systems, and data analysis systems for habitats, health care, manufacturing and science operations) do not exist.

Lack of User Evaluations and Iterative Knowledge Capture
Specific tools and techniques for evaluating human/automation team performance for future missions with varying levels of autonomy, heterogeneity, distribution and mobility do not exist.

Systematic methods and tools for the development and analysis of requirements for automation, and to assist in the building and verifying of prototypes of automation with functional automation logic do not exist.

C. Risk Associated with Poor Task Design

Gaps to be filled to address the risk associated with poor task design include, but are not limited to:

Poorly Designed Tasks and Procedures
Methods of crew training to maximize long term retention and generalization optimized to support both individuals and teams do not exist.

Training strategies for preflight and onboard training for future missions do not exist.

Guidelines and standards necessary for appropriate implementation and use of electronic procedures do not exist.

Current medical checklists do not accommodate rapid assimilation of procedures.

Considerations and guidelines for training for remote medical support do not exist.

Guidelines for the presentation of medical information in support expert decision-making of non-medical expert crewmembers do not exist.

Disregard for Human in Human-Machine System

Guidelines and standards for off-nominal situations that focus training on human performance capabilities and limitations under high stress and workload do not exist.

Guidelines and standards to address the challenges in communication and coordination between distributed parties, especially with off-nominal situations, do not exist.

Training methods for future missions with increased autonomy with appropriate levels of detail that can be tailored to crew's individual learning styles and skill levels do not exist.

Lack of Integrated System Design Approach

Guidelines for appropriate task automation as well as for effective allocation of tasks between humans and machines do not exist.

Clearly defined training standards/methods to support independent decision-making for future missions with increased autonomy do not exist.

VIII. Conclusion

The three SHFE risks are components of a root cause, the lack of human-centered design. This design approach seeks to utilize known information about human capabilities and design to better match those human capabilities, including capitalizing on strengths of the human in the system design while limiting potential impacts resulting from human limitation. This human-centered process focuses heavily on the users through the planning, concept development, design, and final implementation of a product or a system. Good human-centered design practices will result in improved efficiency of operation and safety of all system components, including the human, and should reduce the lifecycle cost of the project.

Each of the identified gaps that relate to the SHFE risks can be attributed to one or more of the seven aspects of poor human-centered design (per Figure 23-1).

- Gaps related to **poorly designed tasks and procedures** demonstrate a constant need for an improved understanding of the crew and the missions they perform the related requirements and constraints and must be properly applied to task design and training.
- **Poorly designed hardware, software**, gaps identify the lack of appropriate design considerations, guidelines and countermeasures for future vehicles including workstations, displays and controls, and general living environments.

- Gaps related to **poorly designed environments and habitats** identify the lack of appropriate design considerations, guidelines and countermeasures for future vehicles including workstations, displays and controls, and general living environments.
- Gaps associated with a lack **of task analysis and understanding of operations** must be filled to ensure awareness of crew and ground personnel functions and how autonomy and automation will be integrated and applied.
- **Disregard for human in human-machine system** gaps reiterates the necessary emphasis on the human as the central focus of the human-centered design process. This process also considers the human's capabilities, limitations and interaction with automation and hardware.
- Gaps related to the **lack of an integrated system design approach** must be filled to ensure quality standards, requirements, tools and techniques are developed to allow for positive crew-system integration and interaction and ultimately mission success.
- Gaps associated with a **lack of user evaluations and iterative knowledge capture** emphasize the need for methods to evaluate human and system performance especially with the expected increased automation and autonomy. This process will help ensure iterative improvements are made to designs as new knowledge is captured and lessons are learned.

Research is needed to assist in developing specific human factors safety analysis techniques and processes that focus on human-centered design implementation. This will assist in the future development of hardware, software and tools better designed to fit the human with the goal of reducing overall human spaceflight safety risks. Research is required to develop more effective information conveyance systems, communication methodologies that are adequately tailored to the human's need and are based on the complete human-machine system and external environmental and operational demands. Human-machine integration issues associated with the introduction of increasingly complex and technologically advanced systems that support life and day-to-day operations need identification. Analysis is needed for smart-automated systems that support the human in high workload and hostile environmental situations.

The gaps related to the three SHFE risks must be addressed. Mapping these gaps to poor design considerations including poorly designed tasks, procedures, hardware, software, habitats and environments; lack of task analysis and operational understanding; disregard for human in human-machine system, and lack of integrated system design approach and user evaluations and iterative knowledge capture demonstrates the need for application of human-centered design throughout all aspects of the design cycle. Guidelines and countermeasures, clearly defined training standards and a better understanding of overall operational capabilities and constraints will assist in the resolution of these gaps, leading to the mitigation of the risks.

IX. References

1. Sanders M, McCormick EJ. Human Factors in Engineering and Design. 7th ed. New York: McGraw Hill; 1993.

2. Hudy C, Woolford B. Space Human Factors Engineering Gap Analysis Project Final Report [document on the Internet]. National Aeronautics and Space Administration; 2007 [cited

2008 Feb 12]. Available from: http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20070020456_2007018857.pdf.

3. Bahr NJ. System Safety Engineering and Risk Assessment: A Practical Approach. Washington DC: Taylor and Francis; 1997.

4. Rosenthal R, Rosnow RL. Essentials of Behavioral Research: Methods and Data Analysis. 2nd ed. Boston: McGraw-Hill; 1991.

5. NASA Flight Crew Integration. ISS Life Sciences Crew Comments Database. NASA Internal Documentation. 2008.

6. Rando C, Baggerman SD, Duvall LE. Habitability in Space. In: Proceedings of the Human Factors and Ergonomics Society 49th Annual Meeting, Aerospace Systems, 2005 Sep 26-30; Human Factors and Ergonomics Society; 2005 p. 5-9.

7. National Aeronautics and Space Administration. Human Spaceflight Gallery [photos on the Internet; cited 2008 Jan 26]. Available from: http://spaceflight.nasa.gov/gallery/index.html.

8. Senior's Story Raises Issue. Lifeboats Stowed in Places Not Easily Accessible. The New York Times [newspaper online]. 1912 Apr 20 [cited 2008 Jan 17]; Available from: http://query.nytimes.com/mem/archive-free/pdf?_r=1&res=9500EEDE103AE633A25753C2A9629C946396D6CF&oref=slogin.

9. Baggerman SD, Rando C, Duvall LE. Habitability and Human Factors: Lessons Learned in Long Duration Spaceflight. Proceedings of the American Institute of Aeronautics and Astronautics Space 2004 Conference Exhibit. 2004.

10. Goodman JR. International Space Station Acoustics. Journal of the Acoustical Society of America. 2000; 108(5): 2475.

11. Allen, CS. Acoustics Issues. In: Barratt MR, Pool SL, editors. Principles of Clinical Medicine for Spaceflight,. Springer-Verlag; 2008. Not yet published. Available: April 11, 2008.

12. Cable News Network. At least 96 Killed in Club Inferno [document on the Internet]. 2003 [cited 2008 Jan 18]. Available from: http://www.cnn.com/2003/US/Northeast/02/21/deadly.nightclub.fire/

13. Farley S. Design Cost Data. Putting an End to the Tragic Equation Codes Seek to Improve Emergency Exit Visibility [document on the Internet]. 2008 [cited 2008 Jan 16]. Available from: http://www.dcd.com/insights/janfeb_2004_dcd_insights.html

14. The Last Voyage of the Lakonia. Time [page on the Internet] 1964 Jan 3 [cited 2008 Jan 23]. Available from: http://www.time.com/time/magazine/article/0,9171,940774,00.html

15. Shayler DJ. Lunar Module checkout-mode error. In : Mason J editor. Disasters and Accidents in Manned Spaceflight. Chichester (UK)P: Springer-Praxis; 2000 p. 216-220.

16. Air Accidents Investigation Branch. Report No: 5/2007. Report on the incident to Airbus A321-231, registration G-MEDG, during an approach to Khartoum Airport, Sudan on 11 March 2005. [document on the Internet]. United Kingdom; 2007 [cited 2008 Jan 17] Available from: http://www.aaib.dft.gov.uk/sites/aaib/publications/formal_reports/5_2007_g_medg.cfm

17. Close-up: The John Denver crash. AV Web, Worlds premier independent aviation news source [page on the Internet]. National Transportation Safety Board; 1999 [cited 2008 Jan 26]. Available from: http://www.avweb.com/other/ntsb9905.html

18. National Transportation Safety Board Factual Report Aviation, NTSB ID: LAX98FA008. National Transportation Safety Board [document on the Internet]. 1999 [cited 2008 Jan 15] Available from: http://www.ntsb.gov/ntsb/GenPDF.asp?id=LAX98FA008&rpt=fa

19. Kranz G. A fire on the pad. In: Failure is not an Option. New York: Simon & Schuster; 2000. p. 191-207.

20. United States Centennial of Flight Commission [photograph on the Internet].Born of Dreams-Inspired by Freedom; 2003. [cited 28 Jan 2008]. Available from: http://www.centennialofflight.gov

21. Meshkati N. Human Factors in large-scale technological systems' accidents: Three Mile Island, Bhopal, Chernobyl. Industrial Crisis Quarterly. 1991; 5: 131-154.

22. Wickens CD, Hollands J. Engineering psychology and human performance. Boston (MA): Addison Wesley; 2000. p. 503.

23. Ellis S. Collision in space. Ergonomics in Design. 2000 8 (1):4-9.

24. Casey S. Set Phasers on Stun and Other True Tales of Design, Technology, and Human Error. Santa Barbara (CA): Aegean Publishing; 1993.

25. Report of the Presidential Commission on the Space Shuttle Challenger Accident. Kennedy Space Center's Science, Technology and Engineering [document on the Internet]. 1986 [cited 2008 Jan 25]. Available from: http://science.ksc.nasa.gov/shuttle/missions/51-l/docs/rogers-commission/Chapter-4.txt

26. Browning, J. B. Union Carbide: Disaster at Bhopal. Bhopal Information Center [document on the Internet]. Union Carbide Corporation; 1993 [cited 2008 Jan 25]. Available from: http://www.bhopal.com/pdfs/browning.pdf.

27. Sturgell RA. Safety recommendation A-07-87 and -88. National Transportation Safety Board [document on the internet]. 2007 [cited 2008 Jan 16] Available from: http://www.ntsb.gov/recs/letters/2007/A07_87_88.pdf.

28. Fact sheet on the Three Mile Island Accident. United States Nuclear Regulatory Commission [page on Internet]. 2007[cited 2008 Jan 25]. Available from: http://www.nrc.gov/reading-rm/doc-collections/fact-sheets/3mile-isle.html.

29. Federal Railroad Association. Positive Train Control Overview [page on the Internet]. 2007. [updated 2007 Nov 16; cited on 2008 Jan 26] Available from: http://www.fra.dot.gov/us/content/1265

30. Railroad accident report, Derailment of northeast Illinois regional commuter railroad train 519 in Chicago, Illinois October 2003. National Transportation Safety Board [document on the Internet]. 2005 [cited on 2008 Jan 16]. Available from: http://www.ntsb.gov/publictn/2005/rar0503.pdf

31. Pipeline accident report, Rupture of piney point oil pipeline and release of fuel oil near chalk point, Maryland April 7, 2000. National Transportation Safety Board [document on the Internet]. 2002 [cited on 2008 Jan 16] Available from: http://www.ntsb.gov/publictn/2002/par0201.pdf

32. The Texas City disaster. April 16, 1947. Texas City Fire Department [page on the Internet]. 2007 Oct 23 [cited 2008 Jan 16]. Available from: http://www.local1259iaff.org/disaster.html.

33. Degani A. Taming Hal: Designing interfaces beyond 2001. New York: Palgrave MacMillian; 2003.

34. Damage Control, Fire Protection Engineering and CBR-D – NAVSEA Naval Sea Systems Command. Gloves with Stowage Bag [page on the Internet]. 2007 [cited on 2008 Jan 25]. Available from: http://www.dcfp.navy.mil/equip/gloves_overhaul.htm

35. United States Navy. USS Cole (DDG 67) Determined Warrior [homepage on the Internet]. 2006 [cited on 2008 Jan 25] Available from: http://www.cole.navy.mil/

36. Sandor A, Holden K. Determining desirable cursor control device characteristics for NASA exploration missions. National Aeronautics and Space Administration. NASA-JSC SF/UTAF report, June 2007. Internal document.

37. Holden KL, Wilmington RP, Whitmore M. Cursor Control Device Evaluations for Space Station Freedom: A Summary NASA Contractor Report 185690. NASA Johnson Space Center. 1992. Internal document.

38. Chiles JR. Inviting disaster: Lessons from the edge of technology. New York: Harper Business; 2002.

39. Adamski AJ, Westrum R. Requisite Imagination: The Fine Art of Anticipating What Might Go Wrong. In: Hollnagel E, editor. Handbook of Cognitive Task Design. Hillsdale (NJ): Laurence Erlbaum Associates; 2003. p. 193-220.

40. Brave men of the USS Forresstal. Naval Aviation News [journal online] 1967 [cited 2008 Jan 25]; October: 6-11. Available from: Naval Historical Center: http://www.history.navy.mil/nan/backissues/1960s/1967/oct67.pdf

41. Rando C, Patel DG, Duvall LE. Use of Cautions and Warnings within International Space Station Procedures: When Too Much Information Becomes Risky. In: Proceedings of the Human Factors and Ergonomics Society 51st Annual Meeting, Safety Potpourri, 2007 Oct 1-5; Human Factors and Ergonomics Society; 2007 p. 1435-1438.

42. Aircraft accident report, Loss of pitch control during takeoff air Midwest flight 5481 Raytheon (beechcraft) 1900D, N233YV Charlotte, North Carolina January 8, 2003. National Transportation Safety Board [document on the Internet]. 2004 [cited 2008 Jan 16] Available from: http://www.ntsb.gov/publictn/2004/aar0401.pdf

43. Pisanich GM, Corker KM, editors. A predictive model of flight crew performance in automated air traffic control and flight management operations. Proceedings of the 8th International Symposium on Aviation Psychology; 1995 Apr 24-27; Columbus, OH.

44. Rice SM. Case Study 1 - Pilot Reach Accommodation. Boeing [document on the Internet]. [updated 2007 Jun 18; cited 2008 Jan 28]. Available from: http://www.boeing.com/assocproducts/hms/index.html.

45. Staff of Anthropology Research Project, Webb Associates. Anthropometric Source Book Vol. I: Anthropometry for Designers (NASA 1024). Washington D.C.: National Aeronautics and Space Administration-Government Printing; 1978.

46. Gilad I, Byran E. Ergonomic evaluation of the ambulance interior to reduce paramedic discomfort and posture stress. Human Factors. 2007; 49 (6): 1019-1032.

47. Hudy C, Byrne V, Smith D, Whitmore M, editors. Human Factors Assessment of Respiratory Support Pack (RSP) Cue Card. Proceedings of the Annual Scientific Meeting of the Aerospace Medical Association; 2005 May 9-12; Kansas City, MO.

48. Medical Device Reporting (MDR) Database. US Food and Drug Administration – Center for Devices and Radiological Health [page on the Internet]. 1995 Jan 27 [cited 2008 Jan 26]. Available from: http://www.accessdata.fda.gov/scripts/cdrh/cfdocs/cfMDR/Detail.CFM?ID=166782

49. Cham R, Redfern MS. Effect of flooring on standing comfort and fatigue. Human Factors. 2001; 43 (3): 381-391.

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XI. List of Acronyms

ATC	Air traffic control
ATU	Audio terminal unit
ATU	Audio terminal units
BHMS	Boeing Human Modeling System
C&W	Caution & warning
CAD	Computer Aided Design
CAU	Cockpit Avionics Upgrades
CBR-D	Chemical, Biological and Radiological Defense
CTAS	Center TRACON Automation System
EGPWS	Enhanced ground proximity warning system
EVA	Extravehicular Activity
FAA	Federal Aviation Administration
FGB	Functional Cargo Block
FMGC	Flight management and guidance
HAI	Human-Automation Interaction
HIS	Human System Integration
HRP	Human Research Program
HTS	Huntington Tri-State Airport
ID	Identify
ILS	Instrument landing system
IMPRINT	Improved Performance Research Integration Tool
IMS	Inventory Management System
IP	International Partners
ISS	International Space Station
KAL	Korean Air Lines

MANPRINT	Manpower and Personnel Integration
MCC	Mission Control Center
MER	Mission Evaluation Room
MIDAS	Man Machine Integration Design and Analysis
MNPA	Managed non-precision approach
NASA	National Aeronautics and Space Administration
NC	Noise Criteria
NURBS	Non-uniform Rational B-Splines
PRD	Program Requirements Document
PTC	Positive train control
QA	Quality assurance
SHFE	Space Human Factors Engineering
SMS	Shuttle mission simulator
TOD	Top of Descent
TRACON	Terminal Radar Approach Control
VPS	Voxel Point Shell
UML	Unified modeling language

APPENDIX 23-A – ADDITIONAL EXAMPLE CITATIONS

Risk of Reduced Safety and Efficiency Due to Poor Human Factors Design

Architecture/Topology

- *Category III evidence of postural changes in microgravity from Skylab-3 and shuttle mission STS-53.* [46]
- *Category II evidence of poor design of the operational environment within an ambulance.*[47]

Environment

- *Category III evidence of poor lighting design on-board the ISS.*[9]

Stowage

- *Category III evidence of an imbalance of supplies launched to the ISS and the ability to dispose of waste and return items to Earth.*[7]
- *Category III evidence of designated stowage areas on-board the ISS exceeding capacity due to limitations on the disposal of packaging materials and waste.*[7]
- *Category III evidence of inefficient stowage of emergency equipment on board the RMS Titanic.*[8]

Hardware and Tool Design and Maintenance

- *Category II and III evidence of spinal elongation from Skylab-4 and the Apollo-Soyuz Test Project.*[5, 46]

Procedures and Training

- *Category III evidence of poorly written and consequently ineffective emergency medical procedures on board the ISS.* [48]

Risk of Error Due to Inadequate Information

Stowage

- *Category III evidence of failure of designers to accommodate consumer stowage practices of medical supplies.* [49]

Human Computer Interaction

- *Category III evidence of failure of hardware and software designers to consider language and culture barriers between the International Partners of the ISS.* [9]
- *Category II evidence from the space shuttle Cockpit Avionics Upgrade evaluation identifies inefficient or inadequate presentation of information to the crew risking crew efficiency and safety.* [44]

Procedures and Training

- *Category III evidence of miscommunications between ground personnel and the crew and a lack of understanding, on the part of ground personnel, of life on the ISS.* [9]
- *Category III evidence of vehicle mode confusion during Apollo 10.* [15]

Risk Associated with Poor Task Design

Environment

- *Category II evidence of failure of workstation designers to consider the operational environment in which workers must stand for long periods of time.* [50]

Human Computer Interaction

- *Category III evidence of vehicle mode confusion resulting in the crash of Eastern Airlines Flight 401.* [38]
- *Category III evidence of inappropriate task allocation and misunderstood automation functions on board China Airlines Flight 006.* [33]

Procedures and Training

- *Category III evidence of poorly designed procedures and task structure results in lost on-board the ISS.*[9]

APPENDIX 23-B – MODELING AND SIMULATION TOOLS DEFINITIONS

- **Jack**- This human simulation system was developed at the Center for Human Modeling and Simulation at the University of Pennsylvania as an ergonomic assessment & virtual human prototyping system for NASA space shuttle development.
- **Computer Aided Design (CAD)** – CAD is mainly used for detailed engineering 3D models and/or 2D drawings of physical components, but it is also used throughout the engineering process from conceptual design and layout of products, through strength and dynamic analysis of assemblies to definition of manufacturing methods of components.
    - **Pro/E** – Pro/E is a3D CAD parametric feature solid modeling software created by Parametric Technology Corporation. It is capable of creating complex 3D models, assemblies, and 2D measured drawings. It originally caused a major change in the CAD industry when first released by introducing the concept of *Parametric Modeling*. Rather than models being constructed like a mound of clay with pieces being added or removed to make changes, the user constructs the model as a list of *features*, which are stored by the program and can be used to change the model by modifying, reordering, or removing them. Pro/ENGINEER is considered a part of the 'High End' 3D CAD modeling packages. Pro/ENGINEER outputs consist of solid model data for tooling and rapid prototyping, manufacturing, and finite element analysis. A product and its entire bill of materials can be modeled accurately with fully associative engineering drawings, and revision control information.
    - **Rhino (Rhinoceros, 2007)** – Rhino can create, edit, analyze, document, render, animate, and translate Non-Uniform Rational B-Splines (NURBS) curves, surfaces, and solids with no limits on complexity, degree, or size. Rhino also supports polygon meshes and point clouds. NURBS are mathematical representations of 3-D geometry that can accurately describe any shape from a simple 2-D line, circle, arc, or curve to the most complex 3-D organic free-form surface or solid. Because of their flexibility and accuracy, NURBS models can be used in any process from illustration and animation to manufacturing.

- **Boeing Human Modeling System (BHMS) (TBD)**- This system provides analysis capabilities of vision & vision obscuration plots, distance analysis, collision detection using Voxel Point Shell (VPS) automated population analysis, reach accommodation, reach envelopes, static volume envelopes and swept volumes using VPS. BHMS has a variety of tools that can be accessed by manikins during simulations analyzing assembly and maintenance tasks. BHMS reach accommodation provides analysis of working populations within a specific work environment. Manikin eye vision provides valuable information during design, maintenance and assembly tasks, it aids in analyzing the feasibility of the maintenance task. A variety of manikin display types are available:
    - The **Enfleshed** (type 0) manikin is fully enfleshed with a 24 Link flexible human spine model with dynamic enfleshment for spine, neck and shoulders,
    - The **Space Suited/EVA** (type 1) manikin is clothed in a NASA Space Suit. Joint limits are modified to model the restrained motion of an astronaut.

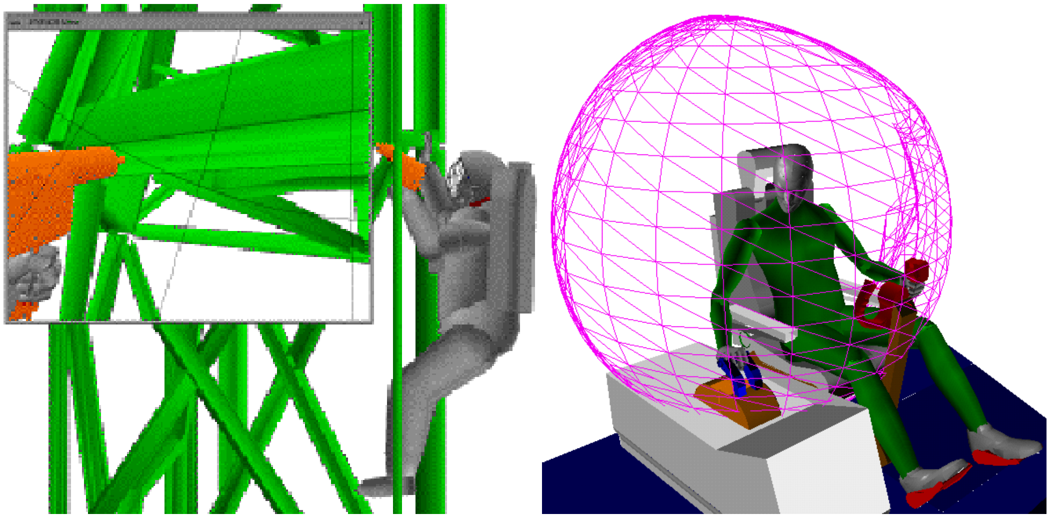
  - The **Stick/Link** (type 2) manikin is represented by a single line for each link in the BHMS manikin link structure. This type is useful when display speed is important and collision detection is not required. This display type includes the 24 link flexible human spine model.
  - The **User Defined** (type 3) manikin allows users to supply custom manikin parts such as heads with helmets, or specialized clothing and shoes. This display type includes the 24 link flexible human spine model with dynamic enfleshment for spine, neck and shoulders.

- **Man-machine Integration Design and Analysis System (MIDAS**) - The U.S. Army, NASA, and Sterling Software Inc. have developed a software system for aiding the design of advanced aircraft cockpits. MIDAS combines graphical equipment prototyping, a dynamic simulation, and human performance modeling with the aim to reduce design cycle time, support quantitative predictions of human-system effectiveness, and improve the design of crew stations and their associated operating procedures.

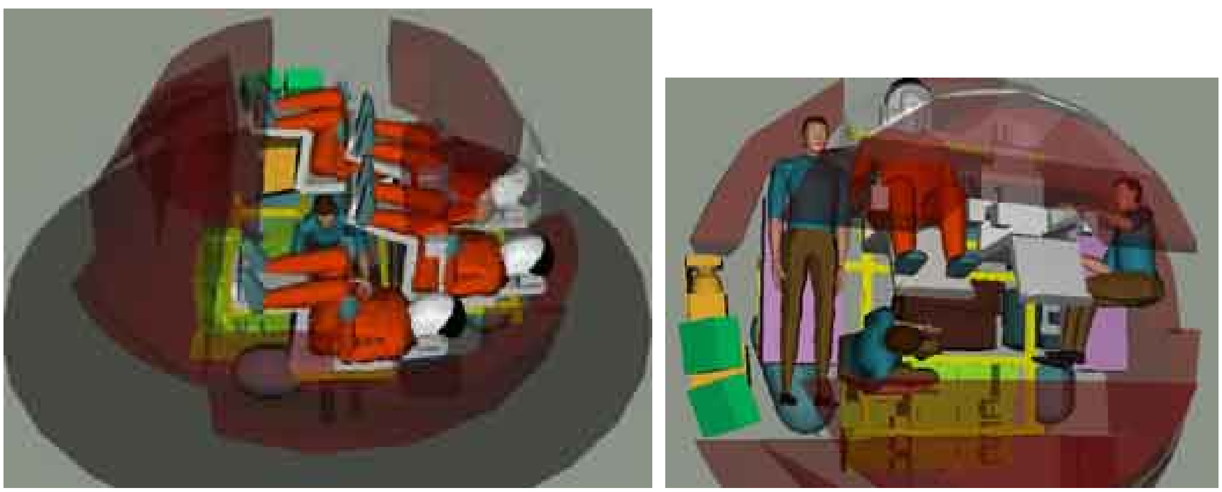
- **Improved Performance Research Integration Tool** (IMPRINT) (United States Army, Research Laboratory, 2005)- IMPRINT is a Human Systems Integration (HSI) and a Manpower and Personnel Integration (MANPRINT) tool developed by the U.S. Army Research Laboratory, Human Research & Engineering Directorate. It is a dynamic, stochastic discrete event network modeling tool designed to help assess the interaction of soldier and system performance throughout the system lifecycle--from concept and design through field testing and system upgrades. IMPRINT may be used in stand alone mode or models may be linked through external communication call protocols such as HLA. IMPRINT is the integrated, Windows follow-on to the Hardware vs. Manpower III (HARDMAN III) tools.

- **Delmi**- This model is a powerful tool used to create, validate, and simulate activities for “workers” using the DPM planning and simulation infrastructure. Workers perform these activities within the PPR environment where they may walk to a specific location (across floors, up ladders, down stairs) based on time parameters defined by the user, move from one target posture to another, as well as pick and place parts in the work area by following the movements and paths of objects. These activities can be combined with DPM Assembly activities to analyze the relationship between workers and other entities within the simulation. They can be simulated and validated using the powerful process simulation capabilities within DPM, allowing the user to test multiple alternatives for the work humans must accomplish in specific manufacturing, maintainability and assembly environments.

- **Unified Modeling Language (UML) - UML** is a standardized specification language for object modeling. UML is a general-purpose modeling language that includes graphical notation.



Examples of Boeing Human Modeling System graphics
(Courtesy Boeing, 2008)



Examples of additional human modeling graphics (Graphics courtesy of NASA)

Human Research Program
Space Human Factors & Habitability Element

Evidence Book

Risk of an Inadequate Food System

March 2008

National Aeronautics and Space Administration
Lyndon B. Johnson Space Center
Houston, Texas

TABLE OF CONTENTS: CHAPTER 24

I. PRD Risk Title: Risk of an Inadequate Food System

Description: Performance is critical for mission success. If the food system does not adequately provide for food safety, nutrition, and acceptability, then crew health and performance and the overall mission may be adversely affected. Furthermore, if the food system uses more than its allocated mission resources, then total required mission resources may exceed capabilities, the mission may be deemed unfeasible, or allocation of resources to other systems may be unduly constrained.

II. Executive Summary

An adequate food system is required to enable safe, reliable, and productive human space exploration. This food system will require the provision of safe, nutritious, and acceptable food to the crew, while efficiently balancing appropriate vehicle resources such as mass, volume, waste, and food preparation time for exploration missions. A dual system (that is a packaged food system with a shelf life of 3-5 years and a bioregenerative food system used on the planetary surface that produces food), is being considered for the Mars missions. Before these missions, it is important to understand the risks to the food system for long-duration missions.

The safety of the food is of highest importance. Any incident of foodborne illness could compromise the success of a mission. Current preflight procedures have ensured food safety. However, as National Aeronautics and Space Administration (NASA) plans for the lunar and Mars missions, new processes will need to be developed to reduce the risk of foodborne illness.

Since the food system is the sole source of nutrition to the crew, a significant loss in nutrition, either through loss of nutrients in the food or inadequate food intake may significantly compromise the performance of the crew. The nutritional content of the food may be inadequate due to losses during processing or due to environmental factors (such as temperature and radiation) over the shelf life of the food. Providing adequate levels of acceptability, variety, and usability is important to prevent inadequate caloric intake.

Ineffective use of vehicle resources such as mass, waste, and crew time can affect mission success. Mass of the packaged food system is based on mass of the food and the packaging surrounding the food. Food packaging produces a significant amount of waste. A bioregenerative food system, while providing the crew with fresh foods, will use more crew time, so the benefit to the crew's performance must be shown to offset the additional burden on the crew.

The paramount importance of the food system in a long-duration manned exploration mission should not be underestimated. The vehicle resources must be balanced with safety, nutrition, and acceptability in order to provide an adequate food system. The food system provides not only the nutrients needed for the survival of the astronauts, but it also enhances the psychological well being of the crew by being a familiar element in an unfamiliar and hostile environment.

This document will present the evidence that supports the Inadequate Food System risk and the knowledge gaps that still remain and need to be filled.

III. Introduction

The primary goal of the Advanced Food Technology Project (AFT) is to develop requirements and technologies that will enable NASA to provide an adequate food system characterized by the provision of safe, nutritious, and acceptable food to the crew, while efficiently balancing appropriate vehicle resources such as mass, volume, waste, and crew time in exploration missions.

Space program food system literature has documented the evolution of the space food system. Several types of food and beverage packaging have been used in NASA space programs. With the exception of Skylab, there has not been a refrigerator or freezer on board dedicated for food storage. Therefore, the food must be shelf stable. This requires inactivation of the microorganisms in the food during ground processing before flight. While processing the packaged foods to commercial sterility provides a safe food system, this level of processing can reduce the quality of the food, including nutritional content and acceptability.

The different forms in which food has been provided include the following:

1. <u>Thermostabilized</u> - This process, also known as the retort process, heats food to a temperature that renders it free of pathogens, spoilage microorganisms, and enzyme activity. Food items are placed into cans or pouches and then heat processed with steam-overpressure or water-overpressure to remove excess air/oxygen for specified times and temperatures to render the food commercially sterile.
2. <u>Irradiated</u> - Irradiation is not typically used to process foods to commercial sterility. However, NASA has special dispensation from the Food and Drug Administration (FDA) to prepare nine irradiated meat items to commercial sterility (1). Irradiation involves the use of gamma rays, x rays, or electrons, and uses energy levels that assure negative induction of radioactivity in the irradiated product. It controls naturally occurring processes such as ripening or senescence of raw fruits and vegetables, and is effective for inactivation of spoilage and pathogenic microorganisms.
3. <u>Rehydratable</u> - A number of technologies are available that allow for the drying of foods. Examples of these technologies are drying with heat, osmotic drying, and freeze drying. These processes reduce the water activity of foods, which results in the inability of microorganisms to thrive.
4. <u>Natural form</u> - Natural form foods are commercially available, shelf-stable foods. The moisture of the foods may range from low moisture (such as almonds and peanuts) to intermediate moisture (such as brownies and dried fruit). These foods rely on reduced water activity in order to prevent microbial activity.
5. <u>Extended shelf-life bread products</u> - Items such as scones, waffles, and dinner rolls can be formulated and packaged to give them a shelf life up to 18 months.
6. <u>Fresh Food</u> - Foods such as fresh fruit, vegetables, and tortillas that have a short shelf life are provided on a limited basis, more for psychological support than as part of meeting dietary requirements.
7. <u>Beverages</u> - The beverages currently being used on International Space Station (ISS) and Shuttle are either freeze-dried beverage mixes (such as coffee or tea) or flavored drinks (such as lemonade or orange drink). The drink mixes are prepared and vacuum sealed inside a beverage pouch. In the case of coffee or tea, sugar or powdered cream can be added. Empty beverage pouches are also provided for drinking water.

One of the goals of the Constellation Program's (CxP) lunar long missions is to use the lunar surface as a test bed for future Mars missions. Although it is possible for CxP to continue using current food technologies, the change in missions will necessitate a change in the food system. The CxP missions will require longer shelf-life packaged foods with improved nutrition and acceptability. These missions will also require more attention to resource utilization including mass, volume, power, crew time, and water utilization. The Mars missions will require technologies to be developed so that the crew is more self-sufficient and less dependant on resupply missions. In addition, once out of low earth orbit, space radiation is higher, and space-irradiated food may lose nutritional content, acceptability, and resource utilization. The research that AFT conducts will allow for the food system to change when necessary.

To further address limitations in vehicle resources to accommodate prepackaged foods, it is also envisioned that once on the lunar or Mars surface, crops would be grown. Fresh fruits and vegetables such as spinach, lettuce, tomatoes, carrots, bell peppers, onions, potatoes, and strawberries could be grown hydroponically in environmentally-controlled chambers. In addition, baseline crops such as soybeans, wheat, rice, peanuts, and dried beans could be grown on the surface or launched in bulk from Earth. These crops would be processed into edible ingredients. These edible ingredients, the freshly grown fruits and vegetables, and packaged food items would be used in preparing meals in the galley. Dependence on the processing and preparation of bioregenerative and bulk commodity foods presents unique risks for these missions.

A mission to Mars will use the prepackaged foods for transit, similar to those used on ISS, and may include positioning food on Mars prior to crew arrival. Prepositioned food may be 3-5 years old at the time of consumption. Currently, prepackaged foods have a stated shelf life of 18 months but will need a 5-year shelf life for the Mars missions. Shelf-life criteria are safety, nutrition, and acceptability. Any of these criteria can be the limiting factor in determining the food's shelf life.

A. Safety

Food safety is defined by quality of food from chemical and microbiological contamination. The food system must be designed to ensure that the initial provisions are safe from contamination and are packaged to remain safe from contamination for up to 5 years of storage in multi-environments. Food safety includes the prevention of microbiological, physical, and chemical contamination of the food, which if not controlled, would put crew health at risk. Good manufacturing practices, which include employee qualifications and training, sanitation, recordkeeping, process validation, and facilities and equipment maintenance and verification, are followed to prevent food contamination during processing and packaging (2).

Microbiological contamination of food can negatively affect crew health and possibly compromise crew survival. Most food items are monitored by the Johnson Space Center's (JSC) Microbiology Laboratory [as specified in JSC-16888 (not publicly available)] to determine that preparation and packaging procedures result in products that conform to established microbial standards for flight foods. Table 24-1 lists the items tested and the associated limits.

Table 24-1. Microbiological Testing for Flight Food Production

Area/Item	Microorganism Tolerances	
Food Production Area	Samples Collected*	Limits
Surfaces	3 surfaces sampled per day	3 CFU/cm2 (Total aerobic count)
Packaging Film	Before use	
Food Processing Equipment	2 pieces sampled per day	
Air	1 sample of 320 liters	113 CFU/320 liters (Total aerobic count)
Food Product	Factor	Limits
Non-thermostabilized**	Total aerobic count	20,000 CFU/g for any single sample (or if any two samples from a lot exceed 10,000 CFU/g)
	Coliform	100 CFU/g for any single sample (or if any two samples from a lot exceed 10 CFU/g)
	Coagulase positive Staphylococci	100 CFU/g for any single sample (or if any two samples from a lot exceed 10 CFU/g)
	Salmonella	0 CFU/g for any single sample
	Yeasts and molds	1000 CFU/g for any single sample (or if any two samples from a lot exceed 100 CFU/g or if any two samples from a lot exceed 10 CFU/g Aspergillis flavus)
Commercially Sterile Products (thermostabilized and irradiated)	No sample submitted for microbiological analysis	100% inspection for package integrity

* Samples collected only on days that food facility is in operation
** Food samples that are considered “finished” product that require no additional repackaging are only tested for total aerobic counts

NASA adheres to the Hazard Analysis and Critical Control Points (HACCP) system, a systematic and preventive approach to food safety that was developed by NASA, the United States Army Laboratory, and the Pillsbury® Company in the 1960’s. Both the Center for Disease Control (CDC) and the United States Department of Agriculture cite the implementation of the HACCP system of inspection as a principal reason why the incidence of foodborne illness appears to be declining (3). The use of HACCP, including the strict use of good manufacturing practices, standard operating procedures, and testing of processed foods, is associated with the prevention foodborne illness events during space missions.

B. Nutrition

Adequate nutrition has two components - necessary nutrients and energy in the form of calories. Without adequate nutrition, there is a risk of not being able to live a healthy, productive life. It is possible to consume enough calories without a well-balanced selection of individual nutrients and produce diseases that are noticeably different from those resulting from an overall insufficiency of nutrients and energy. For example, a vitamin C deficiency may result in scurvy and a deficiency in niacin may result in pellagra. It is important that the crewmembers are provided with the required level of nutrition throughout their missions. Table 24-2 summarizes the required nutritional requirements as stated in the CxP 70024, Human-Systems Integration Requirements document, section 3.5.1.3.1 (not publicly available).

Table 24-2. Nutrition Composition Breakdown

Nutrients	**Daily Dietary Intake**
Protein	0.8 g/kg And ≤ 35% of the total daily energy intake And 2/3 of the amount in the form of animal protein and 1/3 in the form of vegetable protein
Carbohydrate	50-55% of the total daily energy intake
Fat	25-35% of the total daily energy intake
Ω-6 Fatty Acids	14 g
Ω-3 Fatty Acids	1.1 - 1.6 g
Saturated fat	<7% of total calories
Trans fatty acids	<1% of total calories
Cholesterol	< 300 mg/day
Fiber	10-14 grams/4187 kJ
Fluid	1-1.5 mL/4187 kJ And ≥ 2000 mL
Vitamin A	700-900 μg
Vitamin D	25 μg
Vitamin K	Women: 90 μg Men: 120 μg
Vitamin E	15 mg
Vitamin C	90 mg
Vitamin B12	2.4 μg
Vitamin B6	1.7 mg
Thiamin	Women: 1.1 μmol Men: 1.2 μmol
Riboflavin	1.3 mg
Folate	400 μg
Niacin	16 mg NE
Biotin	30 μg
Pantothenic Acid	30 mg
Calcium	1200 - 2000 mg
Phosphorus	700 mg And ≤ 1.5 x calcium intake
Magnesium	Women: 320 mg Men: 420 mg And ≤ 350 mg from supplements only
Sodium	1500 - 2300 mg
Potassium	4.7 g
Iron	8 - 10 mg
Copper	0.5 - 9 mg

Nutrients	Daily Dietary Intake
Manganese	Women: 1.8 mg Men: 2.3 mg
Fluoride	Women: 3 mg Men: 4 mg
Zinc	11 mg
Selenium	55 - 400 μg
Iodine	150 μg
Chromium	35 μg

The ability of the food system to meet the nutritional requirements can only be determined when the nutritional profile of the entire space food system is known at the time when the food is consumed. However, there has only been limited measurement of the nutritional content of the flight food items. Macronutrients and some minerals are determined chemically at the JSC Water and Food Analytical Laboratory (WAFAL). Other nutrients, such as vitamins, are currently calculated with a computerized nutrient database developed by the United States Department of Agriculture (USDA) and the food industry. However, the level of processing done by NASA can reduce the quality of the food, including nutritional content and acceptability. In addition, it is unknown whether processed foods will maintain nutritional adequacy for 3-5 years.

Nutrient losses may occur due to environmental conditions, such as the higher radiation levels during planetary missions. The addition of antioxidants to the food may help prevent the formation of free radicals that contribute to food spoilage (4, 5). In the case of a bioregenerative food system,, radiation may also affect the plants' ability to germinate and grow in the absence of sufficient protection, and it may affect their resulting functionality (4).

During the lunar short missions, it is assumed that Extravehicular Activities (EVAs) will be scheduled no less than every other day for 8-hour periods during lunar surface missions (6). As stated in CxP 70024, Human-Systems Integration Requirements, these EVAs will require no less than an additional 200 kilocalories above nominal metabolic intake, similar in nutrient composition to the rest of the diet, per EVA hour for crewmembers performing EVA operations. Requirements for lunar long or Mars missions have not been determined, but would likely be similar to the lunar short requirements.

C. Acceptability

Food acceptability can be affected by the social context and timing of meals. Food and mealtimes can play a primary role in psychological-social benefit, such as reducing the stress and boredom of prolonged space missions or promoting unity by having dinner together.

Acceptability can be defined in terms of appearance, flavor, texture, aroma, and serving temperature. Currently, flight foods are evaluated using sensory analysis, for acceptability on the ground, by a panel of 30 or more consumers. The products are rated based on appearance, flavor, texture, and aroma using a 9-point Hedonic Scale. Food products must receive an overall score of 6 or higher to be included in the space food system. Similarly, prior to flight, a crewmember will evaluate the foods on a 9-point Hedonic Scale. If their score is less than 6.0, the food item will not be on their personal preference menu.

Product acceptability can be affected by factors such as product formulation, product age, how it is stored, and where it is consumed. Menu variety and usability of the food system also contributes to food acceptability. A large variety of food items is recommended to provide the crew choices and to avoid menu fatigue. If the food is difficult to prepare or eat, then the overall acceptability of the food is reduced (7).

D. Resource Utilization

During the development of a spaceflight food system, several resources have to be considered. These resources include mass, volume, power, crew time, and waste disposal capacity. Misuse of these resources may affect mission success. The balancing of resources with food safety and quality is dependent on the specific mission. For example, the 2-week initial missions to the Moon will consider mission resource utilization more important due to the small usable volume in the vehicle. Since the missions are shorter, nutrition and acceptability may not be as critical.

Food packaging is a major contributor to mass, volume, and waste allocations for NASA missions. Packaging is integral to maintaining the safety, nutritional adequacy, and acceptability of food, as it protects the food from foreign material, microorganisms, oxygen, light, moisture, and other modes of degradation. The higher the barrier properties of the packaging, the more the packaging can protect the food from oxygen and water ingress from the outside environment. Oxygen ingress can result in oxidation of the food and loss of quality or nutrition. Water ingress can result in quality changes such as difficulty in rehydrating the freeze-dried foods.

Currently, the packaging used for the freeze-dried foods and natural form foods does not have adequate oxygen and moisture barrier properties to allow for an 18-month shelf life for ISS. Therefore, those foods are overwrapped with a second foil-containing package that has higher barrier properties. The packaging materials used for the thermostabilized, irradiated, and beverage items contain a foil layer to maintain product quality beyond the required 18-month shelf life. Although the foil layer provides excellent protection, it is not compatible with all technologies that produce commercially sterile foods. For example, two emerging technologies, high pressure processing and microwave sterilization, cannot use the foil package. This will require NASA to either to continue using the foil packaging and forego those emerging technologies, or to acquire packaging compatible with those technologies.

Tables 24-3 and 24-4 list the oxygen and water vapor permeability of the current NASA food packaging materials.

Table 24-3. Oxygen Permeability of Packaging Materials (CC/100IN^2/DAY)

	73.4ºF@100% Relative Humidity
Overwrap	0.0065
Thermostabilized and Irradiated pouch	<0.0003
Rehydratable Lid and Natural Form	5.405
Rehydratable bottom (heat formed)	0.053

Table 24-4. Water Vapor Permeability of Packaging Materials (G/100IN^2/DAY)

	100ºF@100% Relative Humidity
Overwrap	<0.0003
Thermostabilized and Irradiated pouch	0.0004
Rehydratable Lid and Natural Form	0.352
Rehydratable bottom (heat formed)	0.1784

The food system generates both wet and dry waste. Dry waste may include items such as dry food packaging. It is cost prohibitive to plan on launching the trash off the lunar or Mars surface; therefore, another alternative is required for disposal of the trash. Although the foil layer within the food package protects the food from oxygen and water migration, it may provide complications if the decision is made to incinerate the trash on the lunar or Mars surface. Wet waste may include cleaning materials and wet food packaging. Because of spoilage of food substances left on cleaning materials and in packaging, food system wet waste materials must be properly disposed of to limit microbial contamination to the crew.

If the bioregenerative food system is used during the lunar or Mars surface missions, some mass and volume savings will be seen from the use of less packaged foods. However, the processing and preparation equipment will contribute to the mass and volume of the habitat. In addition, the use of this equipment will require more water, power, and crew time then simply heating or hydrating packaged foods. The benefits of bioregenerative food systems will require a vigorous defense if the resources they require are to be allocated on such resource-constrained missions.

IV. Evidence

A. Safety

Good manufacturing practices including microbiological testing of food products before flight have likely prevented foodborne illness. Freeze drying prevents foodborne illness by eliminating the water necessary for microorganisms to grow. Safe freeze-dried foods depend on high quality ingredients and clean surfaces with minimal microorganism contamination at the beginning of the process. However, there still can be viable microorganisms in the food. Therefore, these foods are tested for viable microorganisms before flight. There have been instances where freeze-dried foods did not pass microbiological testing due to contamination from mold, yeast, or bacterial pathogens. It has been reported that 14 items over several years, including chicken salad and shrimp, failed to meet the microbiological specifications (Table 24-1) and hence were not approved for Shuttle and ISS flights (Ott, 2006 Spring Meeting of the American Society for Microbiology Texas Regional Branch, Wimberley, TX). Though this is a small number based on the number of samples that were tested in the JSC Microbiology Laboratory, even one food lot can result in several crewmembers becoming sick during a mission (Evidence Category I).

Thermally processed foods are heated to a high enough temperature for a long enough period of time to provide commercial sterilization. As in the freeze-dried foods, safe foods are still dependent on good HACCP practices. After processing, the thermostabilized pouches are tested for pouch integrity and for swelling to determine whether adequate heat was applied to the food to produce commercial sterility (Evidence Category IV).

B. Nutrition

Crewmembers during Apollo missions often experienced reduced appetite, possibly due to a combination of effects such as fluid shifts, pressure changes, nausea, and work load. In one report the authors stated that the importance of nutrition in the adaptation of astronauts to weightlessness has been recognized since the Gemini program (8). Similarly, it was noted that throughout Mercury, Gemini, and the Apollo missions, weight losses were noticed with few exceptions, including two crewmembers on Apollo 14 (7). Consistently, food intake during these missions was below quantities necessary to maintain body weight. Although the recommended energy intake from the National Academy of Sciences, National Research Council Recommended Daily Dietary Allowances (RDA) is 2,870 kcal/day, the mean energy intake during these missions was only 1,880 ± 415 kcal/day. It was also stated that Apollo nutrition provided only marginal amounts of nicotinate, pantothenate, thiamine, and folic acid (8). The occurrence of arrhythmias in Apollo 15 astronauts was attributed to a potassium deficiency due to inadequate nutrition in the space food system (7). The potassium deficiency in this short-term mission was mitigated in later missions through potassium supplementation. Instances of scurvy, rickets, and other nutritional deficiency conditions occurred in the earlier explorer expeditions due to poor nutrition. Therefore, an unexpected deficiency of one or more nutrients in a long-term space mission may significantly affect mission success (Evidence Category III).

Longer term effects of space travel on nutrition have been documented through physiological changes during the 6-month long ISS Expeditions, where urine, blood, plasma, and serum nutrient contents and body mass were measured postflight and statistically compared to preflight baselines. Of particular concern were the decreased levels of several vitamins and minerals in the urine, blood, plasma, and serum. For example, Vitamin D levels, antioxidant capacity, γ-tocopherol levels, and folate levels were all significantly lower after flight, creating concern for weight loss and associated malnutrition during ISS Expeditions 1 - 8 (9). The results detail the reduced caloric intake (around 80% of recommended intake during spaceflight) leading to an average of a 5% weight decrease and potentially explaining some or all of the measured nutrient decrease. There have been exceptions. Some ISS crewmembers have been able to consume the recommended intakes and have maintained their body mass. It has been suggested that dietary intake may have been low due to time constraints for meal preparation and consumption (9). The Skylab crews, who were required to eat enough to meet their caloric needs, preserved body mass (10) (Evidence Category III). More information on inadequate nutrition through inadequate caloric intake can be found in the Inadequate Nutrition Risk Evidence report.

Inadequate intake is not the only reason for inadequate nutrition. If the food loses nutrients through processing or storage, then the crewmember will not have adequate nutritional intake. Available data on the vitamin content of certain processed foods at various temperatures over 2 years of storage demonstrate the potential for significant vitamin loss (11-15). One report compiled data on the loss of ascorbic acid, riboflavin, and thiamine over 2 years in several canned fruits and vegetables, showing vitamin losses as great as 58% in some canned products held at 80°F, while the same products held at 50°F only showed maximum losses of 38% (16) (Evidence Category I). Therefore, nutritional loss at 3-5 years, which has not been studied, could likely result in inadequate nutrition in the food system (Evidence Category I).

Nutrient changes during processing and over the shelf life of processed foods include isomerization of vitamins or vitamin precursors, changes in bioavailability of amino acids and vitamins as the food structure is broken down, and nutrient degradation, including oxidation of several vitamins and amino acids (17-22). Bioavailability of vitamins may be more important than overall quantity in a food, as other components in the diet and the form of the vitamin may influence absorption and function. Therefore, bioavailability of vitamins in individual foods may vary, making it important to have an understanding of available nutrients as well as overall quantity (17) (Evidence Category I).

There are some emerging technologies that, in the next few years, will be approved by the Food and Drug Administration (FDA) for commercial sterility. The two technologies with most promise are High Pressure Processing (HPP) and Microwave Sterilization. HPP is a method of food processing in which food is subjected to elevated pressures (up to 87,000 pounds per square inch or approximately 6,000 atmospheres), with or without the addition of heat, to achieve microbial inactivation or to alter the food attributes in order to achieve consumer-desired qualities. Pressure inactivates most vegetative bacteria at pressures above 60,000 pounds per square inch. HPP retains food quality, maintains natural freshness, and extends microbiological shelf life (23). Microwave sterilization is a high-temperature, short-time process where the packaged food is cooked at 265^{o}F for 10 minutes (24). The current thermostabilized NASA food products are cooked to about 250^{o}F, but for a much longer time. Preliminary studies suggest that the quality of the foods is much higher using these promising technologies. One investigator determined that food quality (color, texture, etc.) may provide a general indication of nutritional loss of the food (25).

While lower temperatures during storage could help alleviate the storage, ISS and Shuttle missions do not have the mass or power capabilities to provide cold storage (26) (Evidence Category I). Currently, the commercial food industry does not require foods with shelf lives of more than 2 years (Evidence Category III).

C. Acceptability

The acceptability of the food system has been linked to caloric intake and associated nutritional benefits. If the food is not acceptable to the crew, then the crew will not eat an adequate amount of the food and will be compromised nutritionally. Large improvements and advances in space food systems were achieved during the Apollo food program. Nevertheless, the majority of Apollo astronauts did not consume sufficient nutrients. Loss of body weight, fluids, and electrolytes were the rule, with few exceptions (7).

A thorough review of the Apollo experience was provided by Scheuring et al. in a 2007 NASA Technical Memorandum titled “The Apollo Medical Operations Project: Recommendations to improve crew health and performance for future exploration missions and Lunar surface operations” (not publicly available). The objective of the study was to provide evidence to modify medical requirements for future exploration missions by identifying Apollo 7 through 17 mission medical issues. This historical database was generated based on 14 of 22 surviving Apollo astronauts’ responses to 285 questions. Among 11 categories, Food/ Nutrition had 76 responses and 8 recommendations in answering 28 questions. Scheuring et al., in addition to Rambaut et al (8), reported that reduced food consumption may be partially attributed to a combination of physiological effects such as fluid shifts, pressure changes, nausea, issues preparing food, issues with the water system, and work load, but acceptability and familiarity of the food are also critical to consumption. Scheuring et al. also reported that changes in the sensory perception of the food have been noted between ground-based taste tests and Apollo and Shuttle missions, making it important to understand the effect of pressure and fluid shifts on sensory perception. Apollo crewmembers have also stated that having hot water for hot drinks was important, and provided a psychological boost (for example, having coffee in the morning) (Evidence Category III).

Consistently during ISS crew debriefs (documents not available externally due to confidentiality), the crews have stated that their food preferences change from preflight to flight.

It is not uncommon that a crewmember would like something on the ground, but not like it in flight and vice versa. Similar to Apollo and Shuttle, the crews have also noted that their tastes for certain foods change in microgravity and they may crave different foods on orbit as compared to on Earth (Evidence Category III).

ISS crews have noted in crew debriefs that they would prefer more food variety for the length of the missions and they tire of certain foods over 6 months. When the menu cycle repeated after only 8 days (as opposed to the current 16-day menu cycle for ISS missions), the crews noted during debriefs that there was not enough variety in the menu (document not available externally due to confidentiality). Since the diets of the crewmembers during a mission are limited to just those items available, the long-term acceptability may decrease for some of the menu items. It was reported that studies conducted by the armed forces in the 1950's showed that most foods decreased in acceptability when repeatedly consumed. The degree of loss of acceptability depended on the specific food (27) (Evidence Category III).

NASA's next generation space vehicle, Orion, is considerably smaller than the Shuttle and ISS. For that reason, the food system for the Orion vehicle is being challenged with the possibility of no food warmer or no hot water. A study conducted at JSC's Space Food Systems Laboratory in 2006 measured the acceptability of food that was hydrated with ambient water or not heated, even though the food is normally consumed hot. The results showed that the food lost about 20% of its acceptability when consumed at room temperature. About 17% of the food items were determined to be unacceptable based on the current standards of being acceptable if the food scores a 6.0 or better on a 9-point Hedonic Scale. Hence, there is a risk of decreased in-flight nutrition due to lower acceptability and fewer foods available for the mission.

Perchonok and Antonini reported at the 2008 Human Research Program Investigators Workshop (not publicly available) on results of an accelerated shelf-life study of seven thermostabilized items and three bulk ingredients. These items were stored at 40^{o}F (control), 72^{o}F (storage temperature of actual flight food), and 95^{o}F (accelerated temperature). Sensory evaluations were conducted every 4 months for the first 2 years and every 6 months for the third year. The conclusions of the study were that the shelf lives of the thermostabilized items range from 0 months for egg products to 87 months for a meat product. The thermostabilization process does not allow for acceptable products for all formulations. For example, thermostabilized egg products tend to be rubbery and darken in color (28). Meat products have been thermostabilized (canned) for many years and tend to maintain their quality even after processing (Evidence Category II).

Furthermore, if the food preparation takes too much crew time, the consumption of the food may also decrease (7). Providing adequate sensory attributes and ease of use (preparation difficulty and time) with respect to crew scheduling will be necessary to prevent inadequate caloric intake and associated nutritional and psychological issues (Evidence Category III).

It can be concluded that if the food system had adequate levels of acceptability, variety, and usability that the crew would consume more food during their mission.

D. Resource Utilization

Ineffective use of vehicle resources such as mass, waste, and crew time can affect mission success. Mass of the packaged food system is based on mass of the food and the packaging surrounding the food. The mass of the food is dependent on the type of food and the quantity required to meet the crew's caloric requirements. In 1975 it was noted that the mass of the

Apollo 7 food system was at 1.8 pounds of food per person per day (7). By Apollo 14, the mass of the food averaged 2.48 pounds per person per day. The Apollo 8 crew, in 1968, preferred the newly-added thermostabilized foods, referred to as "wetpack foods;" improved crew acceptance of the thermostabilized product justified the weight increase (7). Even with the added "wetpack foods," the Apollo food system was still high in freeze-dried foods since water from the fuel cells was available for food rehydration (Evidence Category III).

Perchonok reported at the 2002 annual meeting of the International Conference of Environmental Systems (not publicly available) that the ISS and Shuttle crewmembers receive about 4 pounds of food plus packaging per person per day. A higher percentage of the food is thermostabilized than on Apollo, due to its higher acceptability. Since ISS uses solar panels for a power source and not fuel cells that produce water as a by-product, there is no mass advantage to using freeze-dried foods. Furthermore, the average number of calories is based on the actual caloric needs of the crewmember based on body weight and height, resulting in an average caloric requirement of 3,000 kcal as opposed to 2,500 kcal provided to the Apollo crew. Based on mass challenges, the CxP is considering the possibility of a food system mass reduction, while still providing the crew with adequate calories (Evidence Category III).

Results in a preliminary study conducted at JSC by French and Perchonok suggested that total mass of the food system may be reduced in a long-duration surface mission if the food system moves more towards a bioregenerative and bulk commodity food system. (The food system used in transit between Earth and Mars would remain a packaged food system, to be compatible with the microgravity environment.). French and Perchonok at the 2006 Habitation Conference reported on a preliminary study titled the Bulk Ingredient Menu project. The project assumed that fresh fruit and vegetables would be grown; however, the mass of the environmental growth chambers was not included in the mass calculations. Some food processing would be conducted using bulk ingredients, such as soybeans into tofu, and wheat would be milled into wheat flour for bread production. The study assumed a 600-day stay on a planetary surface with six crewmembers. French and Perchonok reported that the mass of a food system utilizing food preparation would have a total mass of about 4,200 kg. For the same length of surface stay mission (600 days) and a crew of six, the mass of an ISS-style food system would be about 6,600 kg (Evidence Category I).

Food packaging produces a significant amount of waste. In confidential crew debriefs, the NASA Mir crewmembers stated that the overwrapped foods created a trash management problem since there were two food packages per food item for the rehydratables and natural form foods. Even though the foods are not overwrapped on Shuttle missions, the trash can still be significant. It has been reported that 60% of the mass measured from waste on STS-99 was generated from the food system (including food, drinks, and packaging) while STS-101 demonstrated an even greater percentage of 86% (29). An analysis of the food waste on STS-51D showed a total trash mass of 23 kg that included 12.2 kg of uneaten food and 10.8 kg of food packaging. Eighty–five percent of the trash by volume on STS-29 and STS-30 was food packaging and 7% was food (30) (Evidence Category II).

In 2001, a trade study was conducted to evaluate five potential menus for use during a Mars mission (43). During that study, it was determined that for prepackaged foods, generally 3% of the food would be left in the package if an attempt was made to eat everything. Since packaging is about 9.5% of the mass of the total food system, it would therefore be expected that, at a minimum, 12.5% of the rehydrated food system on shuttle would become waste (Evidence Category I).

To avoid the issues associated with trash accumulation on a lunar or Mars surface mission, the trash will need to be disposed of. One option is to incinerate the trash. However, the foil layer within the food package will not incinerate completely and will leave some ash from the foil (31) (Evidence Category IV).

Several studies have been conducted to determine the effect of a bioregenerative food system on a lunar or Mars mission, with an attempt to balance mass, volume, crew time, and power requirements with nutrition and acceptability. In the trade study conducted in by Levri et al. five menus were evaluated (Table 24-5) using Equivalent System Mass (ESM). ESM converts mass, volume, power, cooling, and sometimes crew time requirements, into one mass value. The volume, power, cooling, and crew time requirements are converted to mass using equivalency factors. These equivalency factors are based on mission length and location.

Table 24-5. Food System Options (Levri et al., 2001)

Case	Food System	Packaging Approach	Crop Growth
1	ISS Assembly Complete (some frozen food)	Individual Servings	Salad
2	Shuttle Training Menu	Individual & Multiple Servings	Salad
3	Shuttle Training Menu	Individual Servings	Salad & White Potato
4	Shuttle Training Menu	Individual Servings	Salad
5	Shuttle Training Menu w/reduced water content	Individual Servings	Salad

The Shuttle Training menu was a menu similar to the Shuttle and ISS food system. The various cases supplemented the Shuttle Training menu with frozen foods, bulk-packaged snack foods and/or salad and/or potatoes. The salad and potatoes would be grown on the Mars surface. Levri et al. determined that if only ESM was considered in choosing a menu, either case 2, case 4, or case 5 would be chosen (Table 24-6). However, they also concluded that non-quantifiable issues (with respect to ESM), such as food palatability and psychological benefits of plant-crew interaction, must come into play in making a decision (Evidence Category I).

Table 24-6. Non-crew time ESM , Crew time ESM and Total ESM (Levri et al., 2001)

ESM	1 (frozen)	2 (multiple serving)	3 (potato)	4(indiv)	5 (reduced water content)
ESM_{NCT}*	27,587	23,246	27,198	23,324	23,351
ESM_{CT}**	4,398	3,635	4,848	3,650	3,654
ESM_{TOTAL}	31,984	26,881	32,047	26,974	27,005

* non-crew time
** crew time

During the Lunar-Mars Life Support Test Project simulation in a closed chamber, a four-person crew tested a 10-day vegetarian diet based on crops expected to be grown during long-duration missions. The crops were processed into ready-to-use ingredients outside of the chamber, leaving general cooking activities and cleanup to the crew. The general preparation and cleaning activities required 4.6 crew hours total per day. The amount of waste, mostly from leftovers, ranged between 20-80%. This experience demonstrated a need for automated processes, a diverse menu, and improvements in recipe scaling based on crew size (32) (Evidence Category I).

French and Perchonok reported at the 2006 Habitation Conference (not publicly available) that the preliminary Bulk Ingredient Menu project determined that food preparation would require for a crew of six about 3 hours per day. However, in addition to the 3 hours, about 6 hours per day of passive time was required for food preparation. Passive time was defined as the preparation time that did not require a crewmember to constantly watch over the process, such as baking. Note that only 30 minutes is set aside for crew preparation on ISS missions (Evidence Category I).

V. Computer-based Simulation Information

Shelf life can be defined as the time when a product no longer maintains the specified quality. Changes in food, whether nutritional or quality, occur through chemical reactions and can be modeled to determine the theoretical shelf life. Actual shelf-life testing is required not only to confirm the rate of reactions, but also to determine which chemical reaction in the food will determine the ultimate endpoint of the shelf life. For example, the endpoint may be the Maillard Browning reaction or the loss of a vitamin.

All chemical reactions in food adhere to the simple general rate equation of

$$-\frac{d[A]}{dT} = k[A]^n$$

where A is the quality attribute being measured, T is the time, k is the rate constant, and n is the reaction order (33). Most quality reactions in food are zero or first order. Zero order reactions have a constant change in quality over time. Typical zero order reactions (n = 0) are enzymatic browning, non-enzymatic browning, and lipid oxidation. Typical first order reactions (n = 1) are protein and most vitamin deterioration, and microbial growth. Although not many reactions in food are second order (n = 2), it has been reported that in limited oxygen, the degradation of Vitamin C is second order (34).

The Q_{10} is a measure of how the rate changes for every 10^{o}C change in temperature. Q_{10} is defined as

$$Q_{10} = \frac{\text{Shelf life at temperature T}^{o}\text{C}}{\text{Shelf life at temperature (T}^{o}\text{C + 10)}}$$

If the color change reaction happens in half the time at 10^{o}C higher temperature, then the Q_{10} = 2 (35).

Since food is not a model system, it is not simple to estimate Q_{10}; however, typical Q_{10} values are shown in Table 24-7. Table 24-7 shows that there is no definitive Q_{10} for a given type of food such that each food must be tested to determine its own Q_{10}. Note that food may have several Q_{10}s. The lipid oxidation may have one Q_{10} value and the Maillard browning may be a different Q_{10} (35).

With Q_{10} values calculated, product shelf life can be projected using the formula:

$t_s = t_0 e^{-aT}$
where:
t_s = shelf life desired
t_0 = shelf at a reference temperature
a = slope of the line equal to $\ln Q10/10$
T = temperature difference between temperature at which the shelf life, t_s, is desired and the reference temperature

Table 24-7. Q_{10} values for various food preservation methods

Food Preservation Method	Q_{10}
Thermally Processed	1 – 4
Dehydrated	2 – 10
Frozen	3 – 40

Shelf life information may be collected at a faster rate using accelerated shelf-life testing and the Q_{10} value. Accelerated shelf-life testing requires a control temperature where no changes are expected to occur through shelf life. The product may also be stored at the current storage temperature and an accelerated temperature, where the reaction rates and resulting shelf life at the accelerated temperature are used to determine the shelf life at the current temperature using the Q_{10} value (35). However, the accelerated temperature may cause changes that would not normally occur in foods at regular storage temperature, such as melting, protein denaturation, and increased water activity (33). These changes must be considered when analyzing shelf-life data.

The complexities of food structure and variety of components make food a dynamic system, which increases the difficulty in quantifying changes with kinetic models. The loss of vitamins to leaching, whether the vitamins are consumed in the leach liquid or not, the loss of nutrients during thermal processing, and the potential for increases in nutrient bioavailability as the food matrix is broken down during processing create an ambiguous picture of the actual nutritional content of processed foods. While the literature attempts to quantify the changes in nutritional content, the answers are not always obvious. However, the literature data provide an estimate for kinetic changes in the space food system and insight into potential countermeasures, such as alternative processing methods and formulation interactions.

While kinetic data are available for the loss of nutrition during processing and storage, the rate constants provided are specific to the food and the conditions in each test (36-41) (Evidence Category I). Therefore, use of the models in the literature will only provide a rough estimate of remaining nutrition if kinetic models were prepared using this data. Accurate nutrition loss data on the thermostabilized pouches specific to the space food system needs to be acquired over a 3-5 year shelf life in order to avoid use of a food system with inadequate nutrition for a Mars mission. Food quality (color, texture, etc.) may provide a general indication of the nutritional loss of the food, as quality factors have similar temperature dependence to many nutrients (25).

VI. Risk in Context of Exploration Mission Operational Scenarios

A. Safety

As long as the use of HACCP (including the strict use of good manufacturing practices, standard operating procedures, and testing of processed foods) continues for packaged flight food approval, foodborne illness events should be prevented during missions. There is always a small risk of foodborne illness during flight. However, once NASA builds the lunar habitat to use as a test bed for Mars missions, and travels to Mars, the source of food may not be limited to only packaged food, and the risk will increase.

During surface preparation of fresh food, safety is no longer ensured as it is through ground operations. Consideration must be given to food safety from microbial, chemical, and physical sources during food processing and preparation on the surface in order to prevent adverse effects on crew health and performance. If the fresh fruits and vegetables are consumed without a heat (cooking) step, there is a potential for food contamination and hence foodborne illness. There may be a need to wash or sanitize. The risk still needs to be quantified for a closed environment, but from 1991 to 2002, there were several produce-related *Escherichia coli* O157:H7 outbreaks reported for field-grown produce (42).

If the packaged food or bulk ingredients are prepositioned on the Mars surface, then there is a risk that the food has been compromised prior to the crews' arrival. Packaging can be torn or the food may be adversely affected by the Martian environment.

Fresh food and bulk ingredients processing and subsequent preparation of meals from the edible ingredients and packaged foods during the long-duration lunar and Mars missions will provide the crew with more variety and fresh foods. However, during these processes, it is necessary to reach a certain temperature/time combination to ensure safety and certain functionality. It is being proposed that the lunar habitat will maintain an 8 psi atmospheric pressure. Heat and mass transfer are affected by partial gravity and reduced atmospheric pressure. At that pressure, the boiling temperature for water is 181^{o}F. Consideration must be given to the changes in environment and the required processing equipment and procedures to ensure safe food processing on a lunar surface.

It is critical to quantify and reduce the risk of food preparation and processing safety prior to use of food preparation and processing on a long lunar mission. This risk could delay a long lunar mission even if all other elements of the mission were ready. Mission loss or major impact to post-mission crew health would likely occur if this risk is not quantified and reduced.

B. Nutrition

Although it is common to see weight loss during the ISS missions, the crews have still been able to perform their duties. The degree of weight loss for the 6-month lunar missions is assumed to be similar to the ISS missions. However, for Mars missions, the food will need to have a shelf life of about 5 years (as opposed to 18 months for the ISS missions) to accommodate the 1,000-day Mars mission. In addition, the packaging will also have to maintain its physical and chemical barrier properties for the 5-year shelf life. Any prepositioning of the food or delay in the consumption of the food will potentially decrease the nutritional content of the food even more. With no resupply options, it is critical to quantify and potentially reduce the risk of inadequate nutritional content of the food prior to the Mars missions. Once the crew begins their mission, they will have no opportunity to mitigate loss of nutrition with resupplied foods or supplements.

The lunar short missions may require each crewmember to perform 8-hour EVAs every other day. If the crew cannot access adequate nutrition during the EVA, the risk of loss of performance can increase.

Unique to space travel are nutrient losses due to space radiation. The extent of loss is unknown; however, one flight study is currently studying the nutritional loss of five food items stored on the ISS for about 2 years. Ground controls are also being analyzed so that the effect of radiation can be determined. There is also the potential for nutritional loss of the chamber-grown fresh fruits and vegetables, as well as the bulk ingredients that may be launched and used for food processing and preparation during surface missions.

The use of bulk ingredients and fresh fruits and vegetables on the lunar and Mars surface can provide the crew with a variety of fresh foods and associated nutrients. These fresh foods should provide at least some of the vitamins that may be lost over time in the processed foods, enhancing the nutritional intake of the crew and associated health and wellbeing, and reducing the risk. However, there is a potential risk that the space radiation may reduce the nutritional content of the food. The processing of the bulk ingredients and preparation of the edible ingredients and fresh vegetables into meals can provide some of the lost nutrients. However, any failure in the growth, processing, and preparation of the foods could increase the risk of loss of nutrition. The overall risk of this type of food system has not been quantified.

C. Acceptability

Acceptability of the food, including variety and usability, though important in the 6-month ISS and Lunar missions, will be even more important in the 1,000-day Mars missions. The acceptability of the food system must be ensured for 5 years, with enough variety and ease of use that the crew consumes adequate quantities throughout this period. With the addition of food processing and preparation during the surface missions, there is an increased risk that the added crew time involved will counteract the increased acceptability of the overall food system. This risk could delay a Mars mission even if all other elements of the mission were ready. Mission loss or major impact to post-mission crew health would likely occur if this risk is not quantified and reduced.

The addition of the freshly grown fruits and vegetables may increase the acceptability of the lunar and Mars missions' food system. These fresh foods would increase the acceptability of the food system by introducing bright colors, crunchy textures, and fresh aromas, encouraging more caloric intake and boosting crew morale by creating a more familiar food system in a hostile and unfamiliar environment.

D. Resource Utilization

The Orion food system is being challenged to reduce the mass due to the smaller vehicle. The high volumes of packaging material required to keep food safe, nutritious, and acceptable, and the power and weight requirements for heating the water and food will need to be minimized to meet the mass challenge. The challenge is to bring the mass from its current level of 4 pounds per crewmember per day to 2.5 pounds per crewmember per day or to the mass of the Apollo food system. However, it is not obvious that this goal is attainable since the Apollo crews were not provided with adequate calories. The galley equipment of hot water and the food warmer are also at risk of being removed from the manifest. If the food mass is not reduced, then other systems may not be able to launch their required equipment.

There is also a risk that the radiation or just age may affect the functionality of the bulk ingredients launched for food processing during a Mars mission. For example, soybean proteins may chemically change resulting in reduced yield in the production of tofu.

As resupply will not be an option for Mars missions, it is especially critical that the food system is robust in its use of resources for 3-5 years. This includes the packaged food system and the bioregenerative food system. There is a risk that the packaged food system may be too high in mass. There is the potential risk of equipment not working or water quantities being inadequate for food hydration, processing, or preparation. There is also the risk that the bioregenerative food system could require too much crew time. There would also be a risk of too much food and packaging waste during a Mars mission.

Constraints on the system could delay a Mars mission even if all other elements of the mission were ready. The risks increase with the increased length of the Mars mission, longer term effects of radiation, especially during transit, and the lack of resupply.

VII. Gaps

A. Safety

1. Why do some freeze-dried foods fail microbial analysis and others do not?
2. What food packaging will provide the correct level of protection of the food for a given mission length?
3. What is the microbial load of chamber-grown fruits and vegetables?
4. What are the allowable sanitation technologies that can be used in an enclosed environment?
5. How does 8 psia affect the mass and heat transfer and how will it affect safety?
6. How does partial gravity affect the mass and heat transfer and how will that affect safety?
7. If food is prepositioned on Mars, how will its safety be ensured?

B. Nutrition

1. How does the thermostabilization process affect nutrition?
2. How does the freeze-drying process affect nutrition?
3. How does the irradiation process affect nutrition?
4. How do the emerging technologies processes such as high pressure processing and microwave sterilization affect nutrition?
5. To what extent does space radiation affect the nutrition of packaged foods?
6. To what extent does space radiation affect the nutrition of bulk ingredients?

7. What in-suit delivery system will provide most effectively the required nutrition for EVAs?
8. To what extent does space radiation affect the freshly grown fruits and vegetables?
9. What are the optimum packaging and environmental conditions to maintain as much nutritional content of the food for the 5-year shelf life?
10. What is the nutritional content of the chamber-grown foods? To what extent does space radiation affect the nutrition of crops grown in enclosed chambers?
11. Can a menu that meets the nutritional requirements be developed from resupply items, freshly grown fruits and vegetables, and processed and prepared foods on a lunar or Mars habitat?

C. Acceptability

1. What food packaging will deliver the highest quality for a given mission length?
2. What food preservation methods should be used to provide the highest quality for a given food formulation?
3. How does a reduced mass food system affect the overall acceptability?
4. What delivery system of the in-suit EVA food will result in high acceptability?
5. What sensory perception changes occur in microgravity?
6. What sensory perception changes, if any, occur in partial gravity?
7. What is the correct level of variety for a given mission length?
8. What affect does mission length have on long-term acceptability?
9. Can a packaged food system maintain its acceptability over a 5-year shelf life?
10. What is the relative acceptability between a packaged food system and a bioregenerative food system? How important are the fresh fruits and vegetables to the overall acceptability of the food system?
11. How does the ease of preparation of the foods for meals affect the overall acceptability of the food system?

D. Resource Utilization

1. How can the mass of the packaged food be reduced?
2. How can food packaging reduce the mass and volume of the packaged food?
3. How can the trash be reduced?
4. What is the optimum ratio of dried and wet foods for a given mission?
5. What packaging material will have high barrier properties to oxygen and moisture, but not contain a foil (aluminum) layer?

6. What modifications to the food processing and food preparation equipment will need to be made to counteract the effect of partial gravity on heat and mass transfer?
7. What modifications to the food processing and food preparation equipment will need to be made to counteract the effect of 8 psia (pounds per square inch absolute) on heat and mass transfer?
8. What food processing equipment should be designed and fabricated?
9. What food preparation equipment should be designed and fabricated?
10. How does space radiation affect the functionality of the bulk ingredients and the harvested fresh fruits and vegetables for food processing and food preparation?
11. How does the age of the bulk ingredients affect their functionality for food processing and food preparation?
12. What level of bioregenerative food system should be used to maintain the correct level of resource utilization, while still providing the required level of nutrition, safety, and acceptability?

VIII. Conclusion

Without an adequate food system, there is a possibility that the crew's health and performance will be compromised. It is clear that in developing future NASA food systems, a balance must be maintained between use of resources (such as power, mass and crew time), and the nutrition and acceptability of the food system to provide an adequate food system. Incorporation of fresh foods, and/or food processing and food preparation during long-duration missions may increase the risk in safety and resource utilization, but may decrease the risk of inadequate nutrition and acceptability.

IX. References

1. The Code of Federal Regulations, Title 21, Food and Drugs, Part 179 (21CFR179). Irradiation in the Production, Processing and Handling of Food. Available online: http://www.accessdata.fda.gov/scripts/cdrh/cfdocs/cfcfr/CFRSearch.cfm
2. The Code of Federal Regulations, Title 21, Food and Drugs, Part 110 (21CFR110). Current Good Manufacturing Practice in Manufacturing, Packing, or Holding Human Food. Available online: http://www.accessdata.fda.gov/scripts/cdrh/cfdocs/cfcfr/CFRSearch.cfm
3. PBS Frontline. 2002. Modern Meat. Available online: http://www.pbs.org/wgbh/pages/frontline/shows/meat/safe/foodborne.html
4. Wilson, L. A.; Perchonok, M. H.; French, S. J. 2007. Influence of Low level Irradiation of Soybeans on the Quality of Soyfoods during Mars Missions. The World of Food Science. Vol. 2. Institute of Food Technologists and the International Union of Food Science and Tech. Available online: http://www.worldfoodscience.org/pdf/WilsonPerchonok.pdf.
5. Gandolph, J.; Shand, A.; Stoklosa, A.; Ma, A.; Weiss, I.; Alexander, D.; Perchonok, M.; Mauer, L. J. 2007. Foods for a Mission to Mars: Investigations of Low-Dose Gamma Radiation Effects. The World of Food Science. Vol. 2. Institute of Food Technologists and

the International Union of Food Science and Tech. Available online: http://www.worldfoodscience.org/pdf/Mauer_Radiation.pdf.

6. NASA. 2005. NASA's Exploration Systems Architecture Study – Final Report. NASA-TM-2005-214062. http://www.nasa.gov/mission_pages/exploration/news/ESAS_report.html .
7. Smith, M. C.; Heidelbaugh, N. D.; Rambaut, P. C.; Rapp, R. M.; Wheeler, H. O.; Huber, C. S.; Bourland, C. T. 1975. Apollo Food Technology. In: Biomedical Results of Apollo (NASA SP-368). NASA, Washington, DC. Available online: http://lsda.jsc.nasa.gov/books/apollo/cover.htm.
8. Rambaut, P. C.; Smith, M. C.; Wheeler, H. O. 1975. Nutritional Studies. In: Biomedical Results of Apollo (NASA SP-368) NASA, Washington, DC. Available online: http://lsda.jsc.nasa.gov/books/apollo/cover.htm.
9. Smith, S.M.; Zwart; S.R., Block, G.; Rice, B.L.; Davis-Street, J.E. 2005. The Nutritional Status of Astronauts Is Altered after Long-Term Spaceflight Aboard the International Space Station. Journal of Nutrition. 135: 437-443.
10. Thornton, W.E.; Ord, J. 1975. Physiological Mass Measurements in Skylab. In: Biomedical Results of Skylab. NASA, Washington, DC. Available online: http://lsda.jsc.nasa.gov/books/skylab/skylabcover.htm .
11. Kamman, J. F.; Labuza, T. P.; Warthesen, J. J. 1981. Kinetics of Thiamin and Riboflavin Loss in Pasta as a Function of Constant and Variable Storage Conditions. Journal of Food Science. 46(5):1457-1461.
12. Kim, Y.-S.; Strand, E.; Dickmann, R.; Warthesen, J. 2000. Degradation of Vitamin A Palmitate in Corn Flakes During Storage. Journal of Food Science. 65(7):1216-1219.
13. Kramer, A. 1974. Storage retention of nutrients. Food Technology. 28:50-60.
14. Lund, D. B. 1975. Effects of commercial processing and storage on nutrients. In: Harris, R. S.; Karmas, E., eds. *Nutritional Evaluation of Food Processing, 2nd Ed.* Westport, CT: The AVI Publishing Company, Inc. pp. 205-243.
15. Pachapurkar, D.; Bell, L. N. 2005. Kinetics of Thiamin Degradation in Solutions Under Ambient Storage Conditions. Journal of Food Science. 70(7):c423-c426.
16. Cameron, E. J.; Clifcorn, L. E.; Esty, J. R.; Feaster, J. F.; Lamb, F. C.; Monroe, K. H.; Royce, R., eds. 1955. Retention of Nutrients during Canning. Research Laboratories. National Canners Association. pp. 79-82.
17. Gregory, J. F. 1996. Vitamins. In: Fennema, O. R., ed. *Food Chemistry*, 3rd Edition. Marcel Dekker Inc.: New York.
18. Chen, B. H.; Peng, H. Y.; Chen, H. E. 1995. Changes of Carotenoids, Color, and Vitamin A Contents During Processing of Carrot Juice. Journal of Agricultural and Food Chemistry. 43:1912-1918.
19. Rock, C. L.; Lovalvo, J. L.; Emenhiser, C.; Ruffin, M. T.; Flatt, S. W.; Schwartz, S. J. 1998. Bioavailability of β-carotene is lower in raw than in processed carrots and spinach in women. Journal of Nutrition. 128(5):913-916.

20. Dewanto, V.; Wu, X.; Adom, K. K.; Liu, R. H. 2002. Thermal processing enhances the nutritional value of tomatoes by increasing total antioxidant activity. Journal of Agricultural and Food Chemistry. 50(10):3010-4.

21. Graziani, G.; Pernice, R.; Lanzuise, S.; Vitaglione, P.; Anese, M.; Fogliano, V. 2003. Effect of peeling and heating on carotenoid content and antioxidant activity of tomato and tomato-virgin olive oil systems. European Food Research and Technology. 216(2):116-121.

22. Seybold, C.; Frohlich, K.; Bitsch, R.; Otto, K.; Bohm, V. 2004. Changes in contents of carotenoids and vitamin E during tomato processing. Journal of Agricultural and Food Chemistry. 52(23):7005-7010.

23. Balasubramaniam VM. HPP Overview. Ohio State University [page on Internet]. 2007 [updated 2007 Oct 18; cited 2008 Feb 12]. Available from: http://grad.fst.ohio-state.edu/hpp/HPPoverview.htm.

24. SSC-Natick Press Release - Microwaves improve processed food quality. US Army Soldiers System Center (Natick) [page on the Internet]. 2004 Mar 4 [cited 2008 Feb 12]. Available from: http://www.natick.army.mil/about/pao/2004/04-06.htm

25. Lund, D. 1988. Effects of commercial heat processing on nutrients. In: Harris, R. S.; Karmas, E., eds. *Nutritional Evaluation of Food Processing, 3rd Ed.* Westport, CT: The AVI Publishing Company, Inc. pp. 319-354.

26. Perchonok, M.; Bourland, C. 2002. NASA Food Systems: past, present and future. Nutrition. 18(10):913-920.

27. Vickers, Z. 1999. Long-term Acceptability of Limited Diets. Life Support & Biosphere Science, 6(1):29-33.

28. Juliano P.; Clark, S.; Koutchma, T.; Ouattara, M.; Mathews, J.W.; Dunne, C.P.; Barbosa-Cánovas, G.V. 2007. Consumer and trained panel evaluation of high pressure thermally treated scrambled egg patties. Journal of Food Quality. 30(1):57–80.

29. Lee, W. C. 2000. Interim report: Advanced life support systems modeling and analysis project: Solid waste handling trade study. NASA. Washington, D. C. Available online: http://els.jsc.nasa.gov/documents/simaDocs/MSAD-00-0501.pdf.

30. Wydeven, T.; Golub, M.A. 1991. Waste Streams in a Crewed Space Habitat. Waste Management & Research. 9:91-101.

31. Perchonok, M.H. 2007. NASA Packaged Food Systems. The World of Food Science. Vol. 2. Institute of Food Technologists and the International Union of Food Science and Tech. Available online: http://www.worldfoodscience.org/cms/?pid=1003820.

32. Kloeris, V.; Vodovotz, Y.; Bye, L.; Stiller, C.Q.; Lane, E. 1998. Design and Implementation of a Vegetarian Food System for a Closed Chamber Test, Life Support & Biosphere Science. 5(2):231-242.

33. Labuza, T. P.; Schmidl, M. K. 1985. Accelerated shelf-life testing of foods. Food Technology. 39(9):57-62.

34. Labuza, T. P. 1982. *Shelf-Life Dating of Foods*. Trumbull, CT: Food & Nutrition Press, Inc.

35. Perchonok, M. 2002. Shelf-life considerations and techniques, In: Sides, C., ed. *Food Product Development Based on Experience*. Ames, IO: Iowa State Press. pp59-73.

36. Evans, S. R.; Gregory III, J. F.; Kirk, J. R. 1981. Thermal Degradation Kinetics of Pyridoxine Hydrochloride in Dehydrated Model Food Systems. Journal of Food Science. 46(2):555-558.

37. Feliciotti, E.; Esselen, W. B. 1957. Thermal destruction rates of thiamine in pureed meats and vegetables. Food Technology. 11:77-84.

38. Mulley, E. A.; Stumbo, C. R.; Hunting, W. M. 1975. A new method for studying reaction rates in model systems and food products at high temperatures. Journal of Food Science. 40(5):985-988.

39. Kirk, J.; Dennison, D.; Kokoczka, P.; Heldman, D. 1977. Degradation of Ascorbic Acid in a Dehydrated Food System. Journal of Food Science. 42(5):1274-1279.

40. Lathrop, P. J.; Leung, H. K. 1980. Rates of Ascorbic Acid Degradation during Thermal Processing of Canned Peas. Journal of Food Science. 45(1):152-153.

41. Rao, M. A.; Lee, C. Y.; Katz, J.; Cooley, H. J. 1981. A Kinetic Study of the Loss of Vitamin C, Color, and Firmness during Thermal Processing of Canned Peas. Journal of Food Science. 46(2):636-637.

42. Aruscavage, D.; Lee, K.; Miller, S; LeJeune, J.T. 2006. Interactions Affecting the Proliferation and Control of Human Pathogens on Edible Plants. Journal of Food Science. 71(8), R89–R99.

43. Levri, J.; Ewert, M.; Kloeris, V.; Perchonok, M.; Peterson, L.; Swango, B.; Toerne, M.; Vittadini, E. 2001. Food System Trade Study for An Early Mars Mission. SAE International Publication #2001-01-2364.

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XI. List of Acronyms

AFT	Advanced Food Technology
CDC	Center for Disease Control
CFU	Colony forming unit
CxP	Constellation Program
ESM	Equivalent System Mass
EVA	Extravehicular Activity
FDA	Food and Drug Administration
HACCP	Hazard Analysis and Critical Control Points
HPP	High Pressure Processing
ISS	International Space Station
JSC	Johnson Space Center
kcal	Kilocalorie
NASA	National Aeronautics and Space Administration
PDR	Program Requirements Document
psi	Pounds per square inch
psia	Pounds per square inch absolute
RDA	Recommended Daily Dietary Allowances
USDA	United States Department of Agriculture
WAFAL	Water and Food Analytical Laboratory

Human Research Program
Space Human Factors & Habitability Element

Evidence Book

Risk of Adverse Health Effects from Lunar Dust Exposure

March 2008

National Aeronautics and Space Administration
Lyndon B. Johnson Space Center
Houston, Texas

TABLE OF CONTENTS: CHAPTER 25

I. PRD Risk Title: Risk of Adverse Health Effects from Lunar Dust Exposure

Description: The risk statement about adverse health effects of lunar dust in the Program Requirements Document is inaccurate and misleading. It refers to rock dust, which is an Earth-based generic term that does not encompass activated lunar dust or the fine size fraction that would be of health concern. Particularly, it does not mention respirable lunar dust (≤ 10 μm), which is the fraction of lunar dust particles that may result in a risk of adverse health effects on the respiratory system. The health risk must also include ocular and dermal effects, especially in view of the tendency of space suits to induce abrasions without any dust present. Dust grains can only exacerbate this effect.

"It is clear that prolonged exposure to rock dust is harmful, but it is not clear if exposure to regolith dust is more or less harmful that terrestrial rock dust. Research into this area may determine if exposure limits need be changed, and/or if additional medical treatment capability is required." – Program Requirements Document

II. Executive Summary

Inhalation exposure to respirable lunar dusts may be toxic to humans; therefore, NASA has determined that an exposure standard is necessary to limit lunar dust. The nominal toxicity expected from ordinary mineral dust may be increased for lunar dust by the large and reactive surfaces of the dust grains. Human exposures to mineral dusts during industrial operations and from volcanic eruptions give us some sense of lunar dust toxicity, although the earth-based analogs have serious limitations. Animal and cellular studies provide further evidence that mineral dusts can be somewhat toxic. Earth-based research of mineral dust has shown that freshly-fractured surfaces are reactive and elicit an increased toxic response. Since lunar dust is formed in space vacuum from highly-energetic processes, we expect the grain surfaces to be reactive indefinitely until the dust is brought into a habitable environment.

Dust from lunar soil carried into the spacecraft during the Apollo missions proved to be a nuisance. The lack of gravity, or existence of gravity at a small fraction of the Earth's gravitational force, increases the time that dust remains airborne, thereby increasing the probability that these dust particles will be inhaled. Lunar dust particles generated by impaction in a deep vacuum have complex shapes and highly reactive surfaces coated with a thin layer of vapor-deposited mineral phase. Airborne mineral dust in a variety of forms has been shown to present a serious health hazard to ground-based workers. Health hazards of volcanic ash, a commonly-used analog of lunar dust, have not been reported to be especially serious; however such ash quickly looses its reactive surfaces and is often aggregated into particles that are not readily respirable into the deep lung.

Crewmembers at a lunar outpost can be directly exposed to lunar dust in several ways: after crewmembers perform space walks (extravehicular activities, EVAs), they will introduce into the habitat a large quantity of dust that has collected on spacesuits and boots. Cleaning of the suits between EVAs and changing of Environmental Control Life Support System filters are other operations that could result in direct exposure to lunar dusts. In addition, if spacesuit design is based on the current design, EVA activities may cause dermal injuries, and the introduction of lunar dusts inside the suits may enhance the abrasions. When the crew leaves the lunar surface and returns to microgravity, the dust introduced into the crew return vehicle will "float," increasing the opportunity for ocular injury.

III. Introduction

*"**In order to guide and focus all efforts to protect the health of the NASA workforce, including space-faring crews, outcome standards and fitness for duty standards will be established and maintained under the direction of the Chief Health and Medical Officer (CHMO).**"*

- *White Paper, Standards Development Process Office of the Chief Health & Medical Officer*

In 2004, President Bush unveiled a plan directing NASA to return humans to the Moon by 2015 and to use the lunar outpost as a steppingstone for future human trips to Mars and beyond. To meet this objective, NASA will build such an outpost on the lunar surface near the South Pole for long-duration human habitation and research. With the various activities of the astronauts going in and out of this habitat on numerous space walks (extravehicular activities, EVAs), the living quarters at the lunar outpost are expected to be contaminated by lunar dust.

The president's Vision for Space Exploration and charge to return to the Moon have resulted in questions about health hazards from exposure to lunar dust. Lunar dust resides in near-vacuum conditions, so the grain surfaces are covered in "unsatisfied" chemical bonds, thus making them very reactive (1). When inhaled, the reactive dust can be expected to react with lung surfactant and pulmonary cells. Thus the weight of evidence is that the fine, respirable lunar dust could be toxic if astronauts are exposed to it during mission operations at a lunar base. Although a few early attempts were made to understand the toxicity of lunar dust obtained by Apollo astronauts or the Luna probes, no scientifically defensible toxicological studies have been performed on authentic lunar dust.

The fact that no accepted health standards or policies exist concerning exposure limits to lunar dust is a critical challenge to the design of vehicle systems in the Constellation program. The multi-center Lunar Airborne Dust Toxicology Advisory Group (LADTAG) was formed and responded to a request from the Office of the Chief Health and Medical Office (OCHMO) to "*…develop recommendations for defining risk criteria for human lunar dust exposure and a plan for the subsequent development of a lunar dust permissible exposure limit.* The LADTAG group, chaired by Dr. John T. James, NASA's Agency Toxicologist, and Dr. Russell L. Kerschmann, Ames Research Center Space Life Science Division Chief, formed a group of technical experts in lunar geology, inhalation toxicology, biomedicine, cellular chemistry, and biology from within the agency along with the nation's leading external experts in these fields. Based on LADTAG's recommendations, NASA's Chief Health and Medical Officer recommended that LADTAG develop a research database on which a defensible exposure limit can be set.

The LADTAG has recommended investigation of the toxicity of lunar dust, to be conducted by the Lunar Dust Toxicity Research Project (LDRTP) for the lungs (pulmonary toxicity), eyes (ocular toxicity) and skin (dermal toxicity), using various assays including in vivo and in vitro methods. In an initial LADTAG meeting in 2005 the experts noted that they were not able to reconcile individual expert opinions in order to set an inhalation standard. The array of opinions from these experts spanned a 300-fold range (0.01 to 3 mg/m^3). The LADTAG concluded that research is necessary to narrow this uncertainty range. The lower end of this range cannot be met by known methods of environmental control, thus there is an urgency to determine the standard so that environmental systems can be appropriately designed. In accord with LADTAG's recommendations, the LDTRP has reviewed first-hand accounts of Apollo astronauts who were exposed to lunar dust during their missions as well as terrestrial-based human exposures in the mining industry and to volcanic ash. In accordance with recommendations to increase our evidence base, LDTRP is conducting studies of Apollo suits, filters, vacuum bags, and rock-collection boxes. These studies will enable us to focus our understanding of the grain-size distribution present in the lunar surface samples and in the habitat, but the dust surfaces are expected to be fully passivated.

IV. Evidence

A. Ground-based Evidence

Ground-based evidence includes data from people exposed occupationally to mineral dusts in industrial settings, from people who live in close proximity to active volcanoes and have been exposed to volcanic ash, and from animals and cells in controlled experimental studies. Mechanistic insights also guide our thinking about the potential toxicity of lunar dusts.

1. Evidence from human exposures during industrial operations

Workers in the mining industry are often exposed to dust from freshly-fractured mineral deposits. When these workers used inadequate or no respiratory protection the consequences were devastating. A prime example of this is the Hawks Nest mining activity in West Virginia beginning in 1927. During the boring of a tunnel, deposits of silica were identified and mined; however, the workers did not use respiratory protection during the operations. Estimates of the proportion of workers that died, often within a few years, are typically about 30% of the 2000 exposed workers (2). This rapidly-lethal form of silicosis has been called as "acute silicosis," which is characterized by alveolar proteinosis and interstitial inflammation (3). The respiratory effects are not exactly like those one would expect from simple silicosis, a disease that usually requires decades to develop after prolonged exposure to lower concentrations of silica dust. The latter disease is characterized by silicotic nodules that are clearly distinct from surrounding tissue, and often surrounded by an inflammatory response (3).

2. Evidence from humans and laboratory animals exposed to volcanic ash

Volcanic ash originates from processes resulting in explosive eruptions into the atmosphere or pyroclastic flows oozing from the surface and discharging ash as they cool, or some combination of these. Under any plausible condition, the ash will have had hours to days to react with the oxygen and water vapor of the atmosphere to passivate all surfaces before being inhaled by humans. The mineral composition of the ash is determined by the composition of the magma. The particle size, mineral composition, and form of the minerals vary considerably from volcano to volcano and from one eruption to another of the same volcano.

Shortly after Mount St. Helens erupted in 1980 a number of experts began to investigate the effects of volcanic ash on those exposed to the dust (4). The crystalline silica content of this dust ranged from 3 to 7%. The primary acute effects were reflected in increased emergency room visits for asthma, bronchitis and eye discomfort (5). The ash was noted to exacerbate chronic respiratory conditions. The increase in hospital admissions lasted approximately 3 weeks (6) and immune parameters were affected even a year later (7). The Montserrat (British West Indies) volcano began erupting in 1995, causing an ash fall from pyroclastic flows that contained 10-24% crystalline silica (8). Childhood wheezing was increased as a result of relatively intense exposures to the ash (9). To our knowledge, sustained long term health effects have not been reported in association with exposures to volcanic ash, although there is speculation that the high cristobalite content of the Montserrat ash could lead to silicosis many years later.

Animal studies that focused on the biological effects of chronic inhalation exposure to Mt. St Helens volcanic ash (or quartz) under controlled laboratory conditions indicated significant dose-response to both materials (10). Quartz was found to be markedly toxic and fibrogenic; by contrast volcanic ash was much less toxic (11, 12). Similar results were observed in other animal studies (13, 14, 15), suggesting that quartz is a much more potent pulmonary toxicant than volcanic ash (12, 14, 15). However, the presence of volcanic ash in the inhaled air did increase the "histamine sensitivity" of the epithelial irritant receptors (13) as well as inhibit the ability of alveolar macrophages to protect against infection (16).

The toxicity of volcanic ashes has been evaluated in rats dosed once by intratrachael instillation (17). Ashes obtained from the San Francisco volcano field in Arizona (lunar dust simulant) and from a Hawaiian volcano (Mars dust simulant) were compared to the toxicity of titanium dioxide and quartz. Lungs of mice harvested 90 days after dosing 1 mg of lunar simulant showed chronic inflammation, septal thickening, and some fibrosis. No changes were seen at the low dose of 0.1 mg/mouse (17). The Martian dust simulant elicited a similar response similar to that of the lunar simulant, except that there was an inflammatory and fibrotic response even at a dose of 0.1 mg/mouse. The response of the mouse lungs to 0.1 mg quartz was comparable to the response to the Martian dust simulant. In another study the effect of these same simulants was assessed on human alveolar macrophages (18). The lunar dust simulant was comparable in cell viability reduction and apoptosis induction to the TiO2 negative control. Both were less toxic than the quartz positive control. Both simulants showed a dose-dependent increase in cytotoxicity.

3. Evidence that surface activation and trace impurities increase toxicity

Inhalation of freshly ground quartz results in a significant increase in animal lung injury when compared to inhalation of aged quartz (16, 19). Freshly ground quartz has increased reactive silicon-based oxygen radicals, and animals exposed to freshly ground quartz are found to have decreased concentrations of antioxidant enzymes (16, 20). Activated quartz particles decay with age in ambient air (20). Quartz dusts containing surface iron as an impurity have been shown to deplete cellular glutathione, contributing to oxidative damage caused by particle-derived and cell-derived reactive oxygen species (21). Castranova (1997) suggests that freshly ground quartz dust contaminated with trace levels of iron may be more pathogenic than quartz dust alone (22).

Crystalline silica exposure studies indicate that the generation of oxidants and nitric oxide plays an important role in the initiation of silicosis (23) and has been shown to cause pulmonary inflammation in rats (24). Other studies indicate that the mode of action of crystalline silica cytotoxicity and pathogenicity lies in the mineral's ability to induce lipid peroxidation (25). Respiratory exposure to freshly ground silica causes greater generation of reactive oxygen species (ROS) from macrophages than exposure to aged silica, this in one piece of evidence that freshly fractured silica is more toxic than aged silica (24, 26).

4. Evidence from mechanistic understandings

Since we know from lunar geologists (level I evidence) that iron is present in lunar dust, especially in the fraction of smallest particles (nano-Fe), one can postulate that a reaction involving iron could be important for activated lunar dust when it comes in contact with the mucous lining of the respiratory system. A good model of the issues and problems associated with testing surface-activated dust can be found in the studies of freshly fractured silica, which is highly toxic to the respiratory system via oxidative damage, and perhaps also in the testing of volcanic ash. The problem of the enhancement of toxicity in quartz by freshly fractured surfaces has been extensively investigated in animal and cellular systems (27, 24, 28, and 29). Fracturing silica cleaves the Si-O bonds, leaving Si' and SiO' radicals, which in turn produce 'OH radicals in an aqueous environment. Aged crystalline silica still produces radicals, but at a much lower level, perhaps by the Fenton reaction between iron and H_20_2 generated by macrophage phagocytosis of the particles (27).

5. Passivation of reactive surfaces as dust surfaces age

Since surface activation, primarily by grinding, is known to increase the toxicity of various mineral dusts, it is critical to ask how quickly surface activation disappears once the dust encounters an oxygen and water-vapor rich environment. By measuring the rate of disappearance of hydroxyl radical formation in aqueous medium from silicon-based radicals on the surface of ground silica, when that ground silica was kept in air until the time of assay, Vallyathan (1988) demonstrated a bimodal decay (26). The half life of the fast decay was approximately 30 hours, whereas even after 4 weeks approximately 20% of the original activity induced by grinding was present on the surface of the quartz. This is similar to the 24-hour half-life in air of freshly-fractured silica’s ability to produce 'OH radicals (27). Although quartz is not lunar dust and grinding is a mere surrogate for activation of dust at the lunar surface, the longevity of the surface reactivity requires careful attention to better understand how surface-activated lunar dust becomes passivated in a habitable environment.

B. Spaceflight Evidence

All spaceflight evidence pertaining to the effect of lunar dust on astronauts is anecdotal (level III). Postflight debriefing reports of the Apollo astronauts serve as a base of evidence (30). Although the astronauts attempted to remove the dust before they reentered the Command Module via brushing of the suits or vacuuming, a significant amount of dust was returned to the spacecraft, causing various problems. For instance, astronaut Harrison Schmitt complained of “hay fever” effects caused by the dust (30), and the abrasive nature of the material was found to cause problems with various joints and seals of the spacecraft and suits (31). In these reports crews provided several accounts of problems with lunar dust exposure:

I. During Apollo 11 crewmembers reported, “Particles covered everything and a stain remained even after our best attempts to brush it off,” a “Distinct pungent odor like gunpowder noted when helmet removed,” and “Texture like graphite” (30).

II. During Apollo 12, regarding dust in the lunar module, the crewmembers noted several issues: “Both LM [lunar module] and CM [command module] contaminated with lunar dust,” and “Lunar Module was filthy dirty and had so much dust that when I took my helmet off, I was almost blinded. Junk immediately got into my eyes”; “The whole thing was just a cloud of fine dust floating around in there.” After docking of the LM to the CM, the dust infiltrated the CM. Crewmembers gave the following account of this period of contamination: “On the way back in the CM the system could not handle the dust, so it was continuously spread inside the spacecraft by the system,” “We chose to remain in the suit loop as much as possible because of the dust and debris floating around,” and “To keep our eyes from burning and our noses from inhaling these small particles, we left our helmet sitting on top of our heads” (30).

III. Apollo 14 crewmembers stated, “Dust was not a problem for us in the cabin” and “The dust control procedures were effective” (30).

IV. The Apollo 15 crewmembers stated, “Cabin smelled like gunpowder when we first came into LM from EVA,” “Particle matter floated around in spacecraft,” “Lunar dust is ‘soluble’ in water,” and “The vacuum cleaner did a good job of clearing the dust from the LM” (30).

V. Apollo 16 crewmembers gave the following accounts: “The LM was extremely clean until the first EVA and then it was extremely dirty”; “I question whether the vacuum cleaner ever worked properly”; “I thought it was quite a hazard over there floating through the LM with all the dust and debris. A number of times I got my eyes full of dust and particles. I felt like my right eye was scratched slightly once” (30).

VI. The Apollo 17 crewmembers stated, “You knew you were in a very heavily infiltrated atmosphere in the LM because of the lunar dust”; “The dust clearing was remarkable considering the amount of dust we had”; “Although there was a lot of irritation to my sinuses and nostrils soon after taking the helmet off, by 2 hours that had decreased considerably”; “I did all the transfer with my helmet off and I am sorry I did because the dust really bothered my eyes and throat. I was tasting it and eating it” and “When I climbed in the tunnel I could tell there was a lot of dust in the LM and you could smell it” (30).

We also have observations of a crew surgeon (Level IV) Dr. Bill Carpentier (32) detailing his own, as well as crewmembers’, postflight allergic-type responses. Dr. Carpentier recalled an increase in eosinophil and basophil blood cell counts post exposure to lunar dust, which may have indicated an allergic response.

No substantive evidence exists that astronaut performance was impaired by lunar dust (31), but one can imagine that if a crewmember were “almost blinded” and had to “remain in the suit loop as much as possible because of the dust and debris floating around,” the dust did have some impact on performance.

Dust from lunar soil carried into the spacecraft during the Apollo missions proved to be a significant, episodic problem. With the return to the Moon and planned extended stays on the lunar surface, the dust toxicity and contamination problems are potentially much more serious. Physical evidence also suggests that lunar dust could be a health hazard at a lunar outpost. Gravity at 1/6 of the Earth’s gravitational force increases the time that dust remains airborne, thereby increasing the probability that these dust particles will be inhaled.

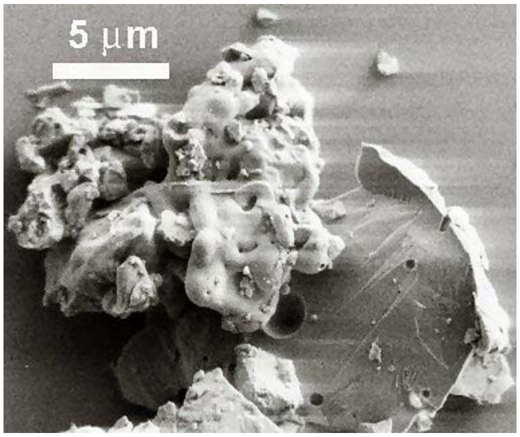
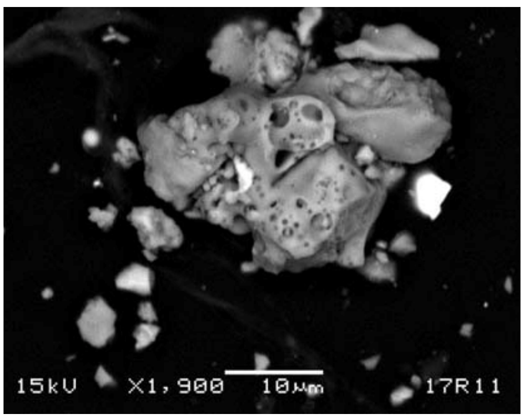


Figure 25-1. Examples of lunar dust grains
LEFT: Scanning electron microscope (SEM) image of a typical lunar agglutinate. Note the sharp edges, reentrant surfaces and microcraters. Smaller grains, less than 1 μm in diameter, are attached to this particle, and are also seen as loose grains in the upper portion of the image. BELOW: SEM image of a lunar agglutinate fragment removed from the outer surface of Harrison Schmitt's EVA suit.



V. Computer-Based Simulation Information

This section is not applicable to this risk.

VI. Risk in Context of Exploration Mission Operational Scenarios

There are multiple, probable scenarios in which crewmembers could be exposed to lunar dust during both lunar sortie and lunar outpost missions. Opportunities for crewmembers to be directly exposed to lunar dust exist after they perform EVAs. Post EVA, crewmembers will introduce into the habitat and lunar lander the dust that has collected on spacesuits and boots. Cleaning of the suits between EVAs may also cause direct exposure to crewmembers. Changing of Environmental Control Life Support System filters is another potential route of direct exposure to lunar dusts. These episodic periods of increased lunar dust exposure must be taken into account when long term exposure limits are calculated. As missions become longer, the greater dose and/or duration of lunar dust exposure will increase the potential human health risk. When a crew returns to microgravity, if dust is introduced into the crew return vehicle, there will be increased opportunity for ocular exposure if particles are floating throughout the cabin. EVA activities cause dermal injuries when suits based on the current design are used, and the introduction of lunar dusts may enhance the injuries sustained from contact with the EVA suit. In addition, NASA is considering a rover design that will allow shirt-sleeve operation of the vehicle. Thus, the vehicle, which must be kept in an interior space to be entered without a suit, may also bring dust into the habitat.

VII. Gaps

1. We do not know the basic toxicity of either activated or fully passivated lunar dust, which will invariably be present in lunar habitats.
2. We do not know how the pristine condition of dust (having reactive surfaces) will affect its toxicity compared to the toxicity of passivated dust.
3. We do not know the rate of passivation of the surface reactivity of pristine dust once it enters a habitat.
4. We do not know how different the dust toxicities will be because of the variations in types of dust present in the habitat (for example, highland vs. mare or mature vs. immature).
5. We do not know how dust toxicity will be affected by the duration of exposure (total load).
6. We do not know how dust toxicity will be changed by changes in particle size distributions and surface areas.
7. We do not know what particle size distribution to expect within the habitat atmosphere (need for forensic engineering)
8. We do not know the mode of action of lunar dust on cells of the respiratory system.
9. We do not know the dermal and ocular toxicity of lunar dust.

VIII. Conclusion

Our evidence base shows that prolonged exposure to respirable lunar dust could be detrimental to human health. Lunar dust is known to have a large surface area (it is porous) and a substantial portion is in the respirable range. The surface of the particles is known to be chemically activated by processes ongoing at the Moon’s surface. We know that this reactivity will disappear on entry into the habitable volume, but we do not know how quickly this will occur, nor do we know how toxic the deactivated dust may prove to be. Although many Apollo astronauts seemed to tolerate lunar dust, their exposures were brief and time-of-exposure factors need to be determined. Other Apollo crewmembers and ground support personnel noted that the lunar dust was troublesome in its persistent presence in the spacecraft and was a sensory irritant. Finally, the size characteristics of the dust that actually was present in the atmosphere of the lunar lander have never been determined. These data will help us understand the size distribution of particles expected in the future lunar habitat. It is important to design experiments to close or at a minimum narrow our knowledge gaps.

IX. References

1. Taylor L, James J. Potential toxicity of lunar dust. *Lunar and Planetary Institute website* http://www.lpi.usra.edu/meetings/roundtable2006/pdf/1008.pdf

2. Cherniack, M. *The Hawk's Nest incident: Americas worst industrial disaster*. Yale University Press,New Haven, CT, 1986.

3. Driscol K, Guthrie G. Crystaline silica and silicosis. In: *Comprehensive Toxicology, Volume 8. Toxicology of the Respiratory System*. edited by Sipes I, McQueen C, Gandolfi A, Roth R. New York: Elsevier Science Inc, 1997.

4. Bernstein RS, Baxter PJ, Falk H, Ing R, Foster L, Frost F. Immediate public health concerns and actions in volcanic eruptions: lessons from the Mount St. Helens eruptions. *Am J Pub Health.* 76: 25-37, 1986.

5. Baxter PJ, Ing R, Falk H, French J, Stein GF, Bernstein RS, Merchant JA Allard J. Mount St Helens eruptions, May 18 to June 12, 1980. An overview of the acute health impact. *JAMA* 246: 2585-2589, 1981.

6. Nania, J, Bruya TE. In the wake of Mount St. Helens. *Ann Emerg Med* 11: 184-191, 1982.

7. Olenchock SA, Mull JC, Mentnech MS, Lewis DM, Bernstein RS. Changes in humoral immu-nologic parameters after exposure to volcanic ash. *J Toxicol Environ Health* 11: 395-404, 1983.

8. Baxter PJ, Bonadonna C, Dupree R, Hards VL, Kohn SC, Murphy MD, Nichols A, Nicholson RA, Norton G, Searl A, Sparks RSJ, Vickers BP. Cristobalite in Volcanic Ash of the Soufriere Hills Volcano, Montserrat, British West Indies. *Science* 283: 1142-1145, 1999.

9. Forbes L, Jarvis D, Pots J, Baxter P. Volcanic ash and respirator symptoms in children on the island of Montserrat, British West Indies. *Occup Environ Med* 60: 207-211, 2003.

10. Wehner AP, Dagle GE, Clark ML, Buschbom RL. Lung changes in rats following inhalation exposure to volcanic ash for two years. *Environ Res* 40: 499-517, 1986.

11. Martin TR, Ayars G, Butler J, Altman LC. The comparative toxicity of volcanic ash and quartz. Effects on cells derived from the human lung. *Am Rev Respir Dis* 130: 778-82, 1984.

12. Martin TR, Wehner AP, Butler J. Evaluation of physical health effects due to volcanic hazards: the use of experimental systems to estimate the pulmonary toxicity of volcanic ash. *Am J Pub Health.* 76: 59-65, 1986.

13. Wiester MJ, Setzer CJ, Barry BE, Mercer RR, Grady MA. Inhalation studies of Mt. St. Helens volcanic ash in animals: respiratory mechanics, airway reactivity and deposition. *Environ Res* 36: 230-40, 1985.

14. Raub JA, Hatch GE, Mercer RR, Grady M, Hu PC. Inhalation studies of Mt. St. Helens volcanic ash in animals. II. Lung function, biochemistry, and histology. *Environ Res* 37: 72-83, 1985.

15. Beck BD, Brain JD, Bohannon DE. The pulmonary toxicity of an ash sample from the Mt. St. Helens Volcano. *Exp Lung Res.* 2: 289-301, 1981.

16. Vallyathan V, Castranova V, Pack D, Leonard S, Shumaker J, Hubbs AF, Shoemaker DA, Ramsey DM, Pretty JR, McLaurin JL. Freshly fractured quartz inhalation leads to enhanced lung injury and inflammation. Potential role of free radicals. *Am J Respir Crit Care Med.* 152: 1003-9, 1995.

17. Lam C-W, James JT, McCluskey R, Cowper S, Balis J, Muro-Cacho C. Pulmonary toxicity of simulated lunar and Martian dusts in mice: I. Histopathology 7 and 90 days after intratracheal instillation. *Inhalation Toxicology* 14: 901-916, 2002.

18. Latch JN, Hamilton Jr RF, Holian A, Lam C, James JT. Toxicity of lunar and Martian dusts simulants to alveolar macrophages isolated from human volunteers. *Inhalation Toxicology* 20:1-9, 2008

19. Shoemaker DA, Pretty JR, Ramsey DM, McLaurin JL, Khan A, Teass AW, Castranova V, Pailes WH, Dalal NS, Miles PR,, Particle activity and in vivo pulmonary response to freshly milled and aged alphaquartz. *Scand J Work Environ Health* 21: 15-8, 1995.

20. Dalal NS, Shi XL, Vallyathan V. ESR spin trapping and cytotoxicity investigations of freshly fractured quartz: mechanism of acute silicosis. *Free Radic Res Commun* 9: 259-266, 1990.

21. Fenoglio I, Fonsato S, Fubini B. Reaction of cysteine and glutathione (GSH) at the freshly fractured quartz surface: a possible role in silica-related diseases. *Radic Biol Med* 35: 752-62, 2003.

22. Castranova V, Vallyathan V, Ramsey DM, McLaurin JL, Pack D, Leonard S, Barger MW, Ma JY, Dulal NS, Teass A. Augmentation of pulmonary reactions to quartz inhalation by trace amounts of iron containing particles. *Environ Health Perspect.* 105: 1319-24, 1997.

23. Castranova V, Porter D, Millecchia L, Ma JY, Hubbs AF, Teass A. Effect of inhaled crystalline silica in a rat model: time course of pulmonary reactions. *Mol Cell Biochem*. 234-235: 177-84, 2002.

24. Porter DW, Barger M, Robinson VA, Leonard SS, Landsittel D, Castranova V. Comparison of low doses of aged and freshly fractured silica on pulmonary inflammation and damage in the rat. *Toxicology* 175: 63-71, 2002.

25. Vallyathan V. Generation of oxygen radicals by minerals and its correlation to cytotoxicity. *Environ Health Perspectives*. 102: 111-115, 1994.

26. Vallyathan V, Shi XL, Dalal NS, Irr W, Castranova V. Generation of Free Radicals from Freshly Fractured Silica Dust: Potential Role in Acute Silica-induced Lung Injury. *Am Rev Respir Dis.* 138: 1213-1219, 1988.

27. Castranova V. Signaling pathways controlling the production of inflammatory mediators in response to crystalline silica exposure: Role of reactive oxygen/nitrogen species. *Free Radical Biol Med.* 37: 916-925, 2004.

28. Ding M, Shi X, Dong Z, Chen F, Lu Y, Castranova V, Vallyathan V. Freshly fractured crystalline silica induces activator protein-1 activation through ERKs and p38 MAPK. *J Bio Chern* 274: 30611-30616, 1999.

29. Vallyathan V, Kang JH, Van Dyke K, Dalal NS, Castranova V. Response of alveolar macrophages to in vitro exposure to freshly fractured versus aged silica dust: The ability of Prosil 28, an organosilane material, to coat silica and reduce its biological reactivity. *J Toxicol Environ Health.* 33: 303-315, 1991.

30. Portree SF, Trevino RC. Walking to Olympus: An EVA Chronology. *Monographs in Aerospace History Series #7,* NASA History Office: 1997.

31. Wagner SA. The Apollo Experience Lessons Learned for Constellation Lunar Dust Management. NASA/TP-2006-213726, Houston, September 2006. http://ston.jsc.nasa.gov/collections/TRS/_techrep/TP-2006-213726.pdf

32. Scheuring RA, Jones JA, Polk JD, Gillis DB, Schmid J, Duncan JM, Davis, JR. The Apollo Medical Operations Project: Recommendations to Improve Crew Health and Performance for Future Exploration Missions and Lunar Surface Operations. *NASA/TM-2007-214755*. Houston 2007.

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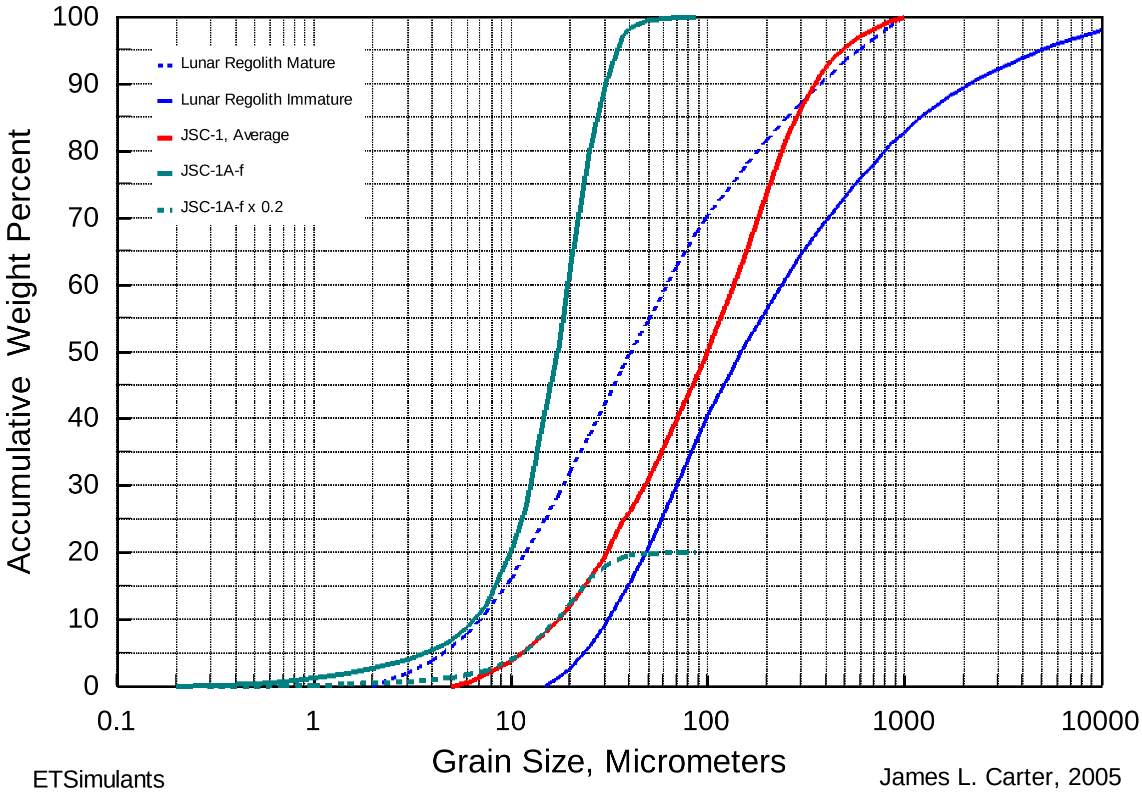
XI. List of Acronyms

CM	Command module
H_2O_2	Hydrogen peroxide
JSC	Johnson Space Center
LADTAG	Lunar Airborne Dust Toxicology Advisory Group
LDRTP	Lunar Dust Toxicity Research Project
LM	Lunar module
Nano-Fe	Iron nanoparticles
NASA	National Aeronautics and Space Administration
EVA	Extravehicular Activity
OCHMO	Office of the Chief Health and Medical Officer
OH	Hydroxyl radical
PRD	Program Requirements Document
ROS	Reactive oxygen species
SEM	Scanning electron microscope
Si-	Silicon radical
SiO-	Silicon dioxide radical
TiO2	Titanium dioxide

APPENDIX 25-A. JSC- 1A SIMULANT WEIGHT PERCENT VS. GRAIN SIZE.



Accumulative Wt. % vs. Micrometers

	Lunar Immature	Lunar Mature	JSC-1 Avg.	JSC-1A-f	JSC-1A-vf
90%	2200	375	360	29	13
50%	148	47	100	18	3
20%	48	12	32	10	1.2
10%	31	6.5	18	6	0.6
5%	24	4.5	12	3	0.3

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